

PACS numbers: 01.60. + q

Gamow in America: 1934 – 1968 (On the ninetieth anniversary of G A Gamow's birth)

A D Chernin

Contents

Abstract. In the years 1934 – 1968, when he worked in the USA, Gamow developed the Big Bang theory and suggested an idea for deciphering the genetic code. These were his main scientific achievements in the period in question. He also tackled the problem of nuclear sources of stellar energy. From 1948 he participated in the construction of the American hydrogen bomb. He wrote over twenty science and popular science books.

In April 1968 Gamov was asked which of his achievements he regarded as the most important. He named the theory of alpha decay, cosmology of the hot Universe, identification of the energy sources of the Sun, and deciphering the genetic code. He also contributed "the formulas used in calculations of the hydrogen bomb". The theory of alpha decay was developed by Gamow back in Russia (this is discussed by V Ya Frenkel', elsewhere in this issue), but all the other scientific achievements listed by him correspond to the 'American' half of his life. During the thirty-four years that Gamow lived in the USA he was involved in many important and interesting pursuits, investigations, events, and meetings. During these years Gamow fully realised his youthful dream: to travel round the world and study physics.

Gamow's autobiography *My World Line* (also discussed in the paper of V Ya Frenkel') stops at 1934, which was the year when he left Europe. His subsequent life is dealt with very briefly, covering a few pages. These pages seem to be a very brief summary or simply a plan of what he intended to describe in detail [1]. Nobody will do this for him now. One can only guess that this would have been a very interesting story. I have therefore set myself the very modest task of recounting, of necessity very briefly, what is known about the life and work of Gamow in America on the basis of his papers and books; reminiscences of his friends, colleagues, and students; and archival sources.

Vera Rubin, now a well-known American astronomer, and in the middle fifties Gamow's postgraduate student at George Washington University, said that "Gamow could not spell; he could not do simple arithmetic. I think it would actually have been impossible for him to find the product of 7×8. But he had a mind that made it possible for him to understand the Universe" [2].

A D Chernin Tuorla Observatory, University of Turku, Finland;
P K Shternberg State Astronomical Institute at the Moscow State University, Vorob'evy gory, 119899 Moscow
Tel. (095) 939 16 22
E-mail: chernin@neptun.sai.msu.su

Received 10 June 1994
Uspekhi Fizicheskikh Nauk **164** (8) 867 – 878 (1994)
Translated by A Tybulewicz

1. Washington, DC

Gamow found himself at George Washington University in the capital, where he was professor for over twenty years (from autumn 1934 to 1956) for the simple and prosaic reason that theoretical physics is cheaper than experiments. The then president of this university, Marvin, wanted modern physics at his institution. However, Merle Tuve, an authoritative experimental physicist from the Carnegie Institute in Washington, told Marvin that equipping a good physical laboratory would require initially at least US$100 000. This would be just the beginning: it would have to be followed by major expenditure if the subject were to be approached seriously. However, physical theories can be developed much less expensively: a theoretician requires a pencil, paper, and naturally expenses for attendances at conferences, but such expenses are necessary in every kind of research.

Marvin asked who could raise physics in Washington to world level. Tuve answered: Gamow [3].

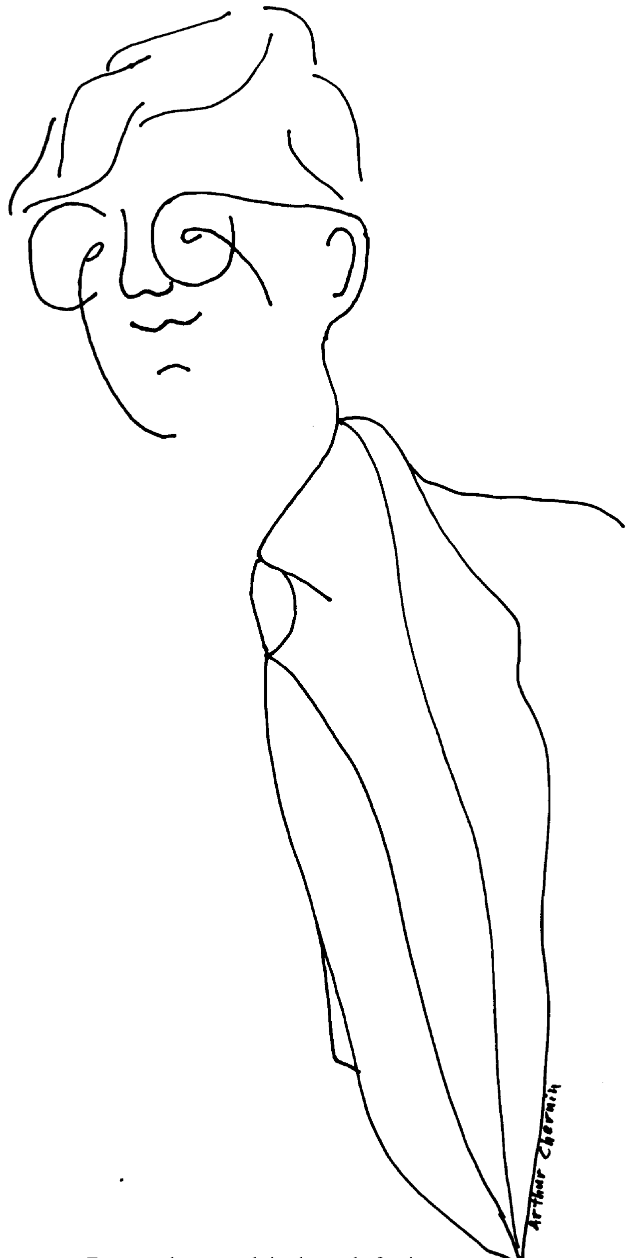
Gamow and his work on alpha decay had long (since 1928) been known to all the physicists in the Old and New Worlds. Tuve, however, knew more. The first attempt to find a place for Gamow in the USA was made by Ernest Lawrence, the constructor of the cyclotron. Lawrence and Tuve were friends, came from the same state (South Dakota), were of the same age, and were colleagues. In the Division of Terrestrial magnetism at the Carnegie Institute Tuve had already constructed a very powerful (at the time) proton accelerator. Lawrence was unable to find a suitable place for Gamow at Berkeley in California. Tuve was undoubtedly aware of the problem and seized the chance for Gamow in the capital. Gamow came to Washington on the understanding that he would give free help to Tuve in the interpretation of his experiments on the scattering of protons by protons.

Gamow himself set two conditions. First, he should be able to organise an annual conference in Washington with the participation of world-leading physicists, similar to the Copenhagen conference organised by Bohr. Second, Gamow insisted that one more theoretician, of his choice, should be invited to Washington so that "I would have someone to speak to about theoretical physics."

The first Washington Conference was held in 1935, a year after Gamow arrived. Before the Second World War it was possible to organise five such conferences, which were attended by Bohr, Fermi, Bethe, Chandrasekhar, Delbruck, and others.

The theoretician invited by Gamow (and also as a professor with the same salary of US$6000 per annum) was Edward Teller, then a 26-year-old temporary chemistry lecturer at the University of London. They became acquainted when visiting Bohr in Copenhagen and went together on an Easter excursion round half of Denmark on Gamow's motorcycle. Teller's biographers say [3] that their discussions on physics in general and about quantum theory in particular during this excursion strengthened even further the authority of Gamow in Teller's eyes. This trip largely determined Teller's subsequent scientific career. The same biographers speak in epic style of Teller's coming to Gamow in Washington: "he stepped onto a path leading to the development of nuclear energy for purposes of war and peace". In fact, Gamow attracted Teller to nuclear physics from molecular chemistry, with which he had been occupied until then.

Gamow was not the first major physicist who came in the thirties from Europe to the USA. Einstein arrived in America a year before. He was soon followed by many others. Possibly, already in 1933 Gamow understood that once he left Russia, he would not be able to stay long in the Old World and therefore decided to cross the Atlantic as soon as possible. The post of a professor at a university in the capital, the ability to invite Bohr and others to his conferences, and continuous cooperation with Teller and Tuve was a fitting beginning to Gamow's American life.



From a photograph in the early forties.

2. Stellar energy forces

The nuclear origin of the stellar energy had been guessed by Eddington in his book *The Internal Constitution of the Stars*, first published in Cambridge in 1925. In this book Eddington even specified the actual nuclear reaction which could provide the necessary energy in the interior of the Sun and other stars: the conversion of hydrogen into helium. At the time it was known that the mass of the nucleus of the helium-4 atom is approximately 1% less than the total mass of four hydrogen nuclei (protons). (Eddington used the results of Aston's experiments, which gave the value of 0.8% for this difference; this was later refined to 0.7%.) In each such conversion the energy released would be $E = mc^2$, where m is the difference between the masses, known as the mass defect.

However, it was clear to all that such a reaction would require a very close approach of protons to distances at which the nuclear forces would act. Simple estimates have shown, however, that the probability of such close encounters is practically negligible: the Coulomb repulsion between protons excludes almost completely the possibility of an approach at temperatures of 10–20 million kelvin, typical of the stellar cores. Eddington ignored this difficulty and said: "We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a *hotter place*." (When this famous prediction is cited in Russian, it is regarded as essential to explain — as was done, for example, by Zel'dovich — that the 'hotter place' is hell.) Quantum mechanics saved Eddington from these critics. More exactly, the approach is possible because of the tunnelling of particles across a potential barrier.

Gamow used this effect to account for the origin of alpha decay and his friend Houtermans (who learned about this from his conversation with Gamow in Copenhagen) postulated together with Atkinson the tunnelling to calculate the probability of mutual approach of protons to very short distances in the interior of the Sun and stars. The work of Houtermans and Atkinson, published in 1929, removed the difficulty which was (quite arbitrarily but perfectly correctly) ignored by Eddington: he produced no arguments in support, apart from the bold prediction given above, and such arguments could not have been provided until Gamow did this in 1928. Fortunately, all was resolved some three years later.

About a decade passed before Gamow and Teller (in 1938) were able to throw more light on the subject. During this decade nuclear physics has seen the discoveries of the positron, neutron, and deuteron. Extensive new experimental data have been accumulated on the cross sections of the nuclear reactions. As a result, Gamow and Teller increased the key number in the calculations of Atkinson and Houtermans by a factor of ...1000! A year later Bethe and Critchfield (Gamow's student) finally solved the problem by developing the theory of the proton–proton cycle in stars. They used the theory of beta decay just proposed by Fermi and improved by Gamow and Teller.

The proton–proton cycle is a chain of five reactions (since 1951 it has become clear that one should add a sixth reaction) in the course of which the following nuclei are produced and then used in the formation of helium-4: deuterium, helium-3, beryllium-7, and lithium-7. This process is the main source of energy in the Sun and other stars less bright than the Sun.

In the case of brighter stars (such as, for example, Sirius), energy is produced in them as a result of a more complex and longer chain of transformations in which carbon and nitrogen participate as catalysts. These transformations, called the carbon–nitrogen cycle, were discovered by Bethe in 1938.

Bethe carried out the main calculations on this topic during his return journey from the next Washington Conference to which Gamow, Teller, and Tuve invited both physicists and astronomers. The topic of this Conference was the origin of stellar energy. As Gamow tells it [1], on arrival in Washington Bethe knew all about the nuclei of atoms and nothing about the interior of a star. During this Conference and soon after Bethe wrote (together with Critchfield) the paper mentioned above on the proton–proton cycle. Critchfield began his work by calculation a year before, on the suggestion of Gamow, but he encountered mathematical difficulties. Gamow could not help him: Gamow did very well without mathematics, but he could not stand complex calculations. Bethe readily solved the problem as soon as Gamow explained what was involved.

Almost thirty years later, in 1967, Bethe received the Nobel Prize for physics for his work on the nuclear sources of stellar energy. Some think that this prize should have been shared with another nuclear physicist, C F von Weizsacker, who discovered the carbon–nitrogen cycle simultaneously with Bethe and indepently of him. However, von Weizsacker was not forgiven for his work during the War on the German atomic bomb (which was never produced).

Gamow joked that he played the role of a catalyst in the history of nuclear sources of stellar energy; he managed everything and he left in the same state as he entered, like carbon in the Bethe cycle.

3. At the threshold of the atomic age

The 1939 Washington Conference was planned by Gamow, Teller, and Tuve to be on the subject of low-temperature physics. The plans had to be abandoned. Bohr arrived at the conference from Europe with the latest news of exceptional importance. At the end of 1938 O Hahn and F Strassmann discovered barium isotopes among the decay products of uranium, heaviest among the then known elements. The decay occurred as a result of bombardment of uranium with neutrons. O R Frisch and Lise Meitner (who was Frisch's aunt) correctly interpreted this experimental discovery: the key word was 'fission' introduced by Frisch.

In January 1939 the physicists who met in Washington for the Gamow Conference realised with surprise that a new era had started in science and possibly in the history of humankind.

Uranium replaced low temperatures as the topic at the conference. Discussions involved not only Bohr, Gamow, and Teller, but also Fermi, who had just arrived in the USA from Stockholm with the 1938 Nobel Prize for physics for the experimental investigations of the induced (artificial) radioactivity caused by neutron bombardment of nuclei. At the end of the conference, on 28 January, Tuve demonstrated experimentally the fission of uranium in his laboratory: theoreticians could see 'fission live' with their own eyes.

The subsequent events occurred at an increasing pace. In the same year, 1939, Bohr and J A Wheeler developed a detailed quantitative theory of the decay of uranium as a result of neutron capture. They used the formula for the mass defect of nuclei proposed in 1930 by Gamow and improved in 1935 by von Weizsacker. Following Bohr and Wheeler, an estimate of the mass defect and, most importantly, the energy yield of the decay of uranium was made in 1940 by Frisch and Peierls. These showed that a bomb of enormous destructive power can be based on the process. Earlier, Szilard in the USA and Khariton and Zel'dovich in the Soviet Union put forward the idea of a nuclear chain reaction. Soon after, open publications on the 'uranium problem' stopped. It became clear that the development of a nuclear weapon was imminent.

In the famous report by Smyth [4] on the development of the American atomic bomb, published in the autumn of 1945 immediately after Hiroshima, a systematic account is given of the scientific and technological work carried out in the USA on a huge scale in 1940–1945. All the leading physicists already present in the USA took part in this work: for the convenience of readers Smyth gave a full list of names. However, only Gamow is missing from this list.

Although Smyth mentions Einstein (the letter from Einstein to President Roosevelt provided the stimulus for the USA nuclear programme known as the 'Manhattan Project'), he did not work on the bomb. Einstein and Gamow were left out of the grandest scientific and technological enterprise which history had known up to that time. They were probably excluded for 'reasons of security'. Nobody knows what these reasons were. Einstein's biographers have provided nothing concrete on the topic: although such a long period of time has passed, information of this type is not accessible to science historians in the USA. The same applies to Gamow (whose biography has yet to appear in the USA).

There are at least two hypotheses relating to Einstein's exclusion from the Manhattan Project. According to one of them, he was kept away from the scientific work on the atomic bomb so that he could not use his enormous prestige to interfere subsequently in the political decision on its use [5]. Moreover, as a person he was far too unconventional for intelligence services; an eccentric in his personal life, world-famous, capable of communicating directly with the President of the USA. Add to this his reputation as an atheist and perhaps even a Communist. A similar hypothesis can be put forward about Gamow: he was also an eccentric with the world fame of a major physicist. Moreover, he was Russian.

Both Einstein and Gamow did everything in their power to help the victory over the Nazis. This has never been in doubt. The fate, mediated by the US Navy, brought them together during the war for cooperation on subjects which were of secondary importance.

4. Walks with Einstein

Einstein was invited to work as a consultant on the technical aspects of war relating to 'conventional' (i.e. nonnuclear) explosives. Gamow brought the topics for discussion from Washington to Princeton. Einstein and Gamow were acquainted and the US Navy headquarters in Washington decided that together they could do something useful: if asked specific questions, they could provide expert opinion on small projects.

Einstein and Gamow met in Princeton once every two weeks and before lunch they dealt with these 'naval matters'. Then they walked, and talked about science. During one of these walks Gamow told Einstein about Jordan's idea that stars may form from a vacuum on condition that in their 'initial state' they are very strongly compressed. If in this state the absolute value of the rest energy of a star is equal to its gravitational potential energy, the creation process is not forbidden by the laws of conservation. Gamow recounts [1] that, hearing this, Einstein stopped: he was obviously perplexed and lost deep in thought. Gamow and Einstein were then crossing a road with heavy traffic and some cars had to stop and wait until Einstein began to move again. Since then the theoreticians began to talk of the creation of not only stars but whole universes from nothing on the basis of general relativity.

Einstein and Gamow also discussed cosmological problems. Einstein probably was interested in the personal details of Friedmann who disproved Einstein's concept of a static Universe and became the founder of the expanding Universe cosmology. Gamow was proud to have been a student of Friedmann in 1922 – 1925 in Leningrad. For his model of the static Universe, Einstein invented in 1917 what is known as the cosmological term. Later, Einstein came to regard this as his major blunder in science and he told Gamow this during one of their Princeton walks. Gamow commented that the 'errors' of a genius are still part of a genius. The cosmological term once invented cannot be struck out from science.

The expanding Universe solution, derived by Friedmann from Einstein's equations, allows for the possibility of the cosmological term, which in Friedmann's case can be positive, negative, or zero. It would appear that without the cosmological term the correct age of the Universe of $(15-20) \times 10^9$ years would not have been obtained in modern cosmology. Moreover, we cannot exclude the possibility that the very expansion of the Universe owes its origin to the cosmological term. Expressed in a different way, the effect of the cosmological term can be regarded as the existence of a universal vacuum uniformly filling all space. This was noted in the sixties by E B Gliner and later gave rise to the popular 'inflation theory'. The background of such inflation, i.e. an exponentially fast expansion under the action of the antigravitation of a vacuum (corresponding to a positive cosmological term) is nowadays used to consider the possibility of multiple creation of universes or 'baby universes', which is the name used by Stephen Hawking, who is the greatest enthusiast of the idea.

Gamow noticed many randomly scattered sheets with tensor formulas in Einstein's study at home. Gamow had thought that this meant that Einstein continued to work stubbornly on his unified field theory. However, neither Gamow nor Einstein referred to this subject in their talks.

What did Einstein and Gamow think about their ambiguous positions? Did they discuss this during their walks? Did they touch upon problems of more general nature? We do not know and most probably we shall never learn.

5. The bomb

In summer 1948 Gamow was informed that he could now work on subjects involving state security. He joined the research team at the Los Alamos Laboratory working on the construction of the American hydrogen bomb. The key figure here was his old friend Teller, who right from the beginning was one of the leaders in the nuclear weapons programme of the USA. In Teller's biography [3] one can read that "Teller credited George Gamow, his colleague from George Washington University, with initiating the theoretical work in the United States that ultimately led to the biggest manmade explosion". Let us follow this with another direct quote from Teller.

"Now, Gamow had a fertile imagination. He was an exceedingly nice guy, and furthermore, he was the only of my friends who really believed I was a mathematician... Now, I'm sorry to say that ninety percent of Gamow's theories were wrong, and it was easy to recognize that they were wrong. But he didn't mind. He was one of those people who had no particular pride in any of his inventions. He would throw out of his latest idea and then treat it as a joke. He was a delightful person to work with."

This is actually all that we can say about Gamow's work on the American hydrogen bomb. What were the 10% of his ideas that remained after 90% were rejected? "Formulas used in...", as I quoted Gamow at the beginning of this paper. We do not know what formulas Gamow thought of in Los Alamos or brought from Washington.

Let us cite Teller again. During the same Los Alamos years he called the theoretical work on the thermonuclear reactions 'Gamow's game' and he regarded Hans Bethe as a champion of this game.

Gamow himself said (in his usual way) that his main contribution to the American hydrogen bomb was that he brought Teller to America.

Gamow indeed seemed to turn practically everything into a joke. But willy-nilly he had to deal with matters which were far from a joke. This is true, for example, of the story of Teller as the 'father of the American hydrogen bomb' testifying against the 'father of the American atomic bomb' (Oppenheimer) in front of the Atomic Energy Commission of the USA, which then removed Oppenheimer from secret work. Gamow regarded the charges against Oppenheimer as irrelevant. I would like to know Gamow's feelings at the time when the well-known ultraconservative USA senator suspected of treason practically every university professor, writer, or diplomat. However, we do not know anything about this.

What is known with certainty is that Gamow, working on the most powerful of man-made explosions, was thinking of the origin of the greatest explosion in nature, which is the expansion of the Universe.

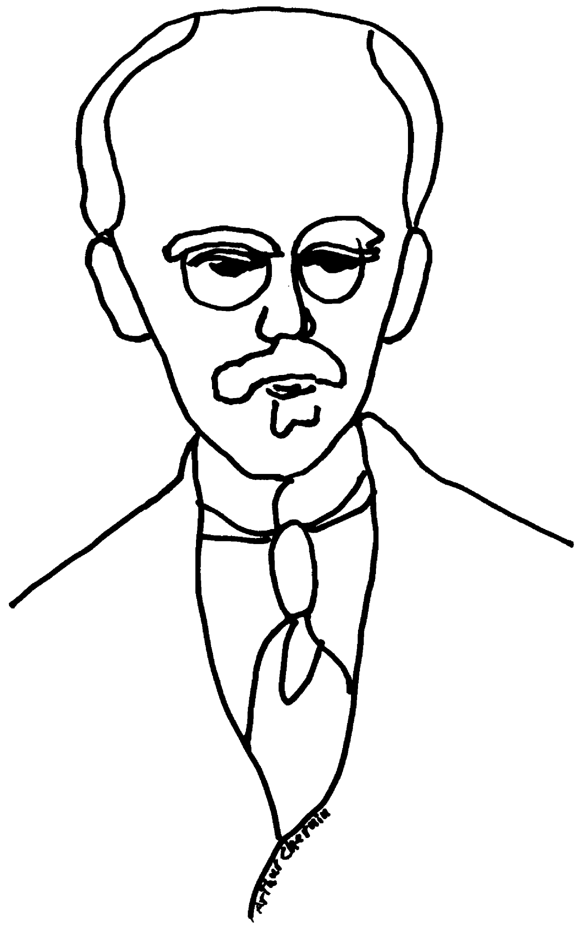
6. The Big Bang

Gamow never forgot cosmology, the science of his youth. He returned actively to the subject in 1946, two years before Los Alamos, and devoted a decade to it. His aim was to bring nuclear physics into cosmology. He had the experience of combining astronomy with the physics of the nucleus in his work on nuclear sources of stellar energy. He followed the trail of Eddington, Atkinson, and Houtermans, but the mature product of this activity came from Bethe.

However, in cosmology he had no 'nuclear' forerunners: he was the first and he took the subject to its completion. As a result, he came to witness the excellent fruit of his bold and elegant idea, right to the news that the background or relic radiation he predicted had been discovered. Thus the combination of geometry and dynamics in Friedmann's model with nuclear physics (and thermodynamics) led to the present-day cosmology, the Big Bang theory.

In my paper, which is a contribution to the history of science and has been written to celebrate an anniversary, I shall not attempt to give in any sense a detailed account of Gamow's theory. Tens of books and thousands of papers have been written on the subject. Reviews on cosmology are published regularly in *Uspekhi Fizicheskikh Nauk*. The first review, based on Friedmann's theory, was written many years ago by M P Bronstein, a friend of young Gamow in Leningrad [6]. Zel'dovich was the first to write a review of Gamow's theory immediately after the discovery of the background radiation [7]. This review of Zel'dovich was noted by Gamow, who responded with a warm personal letter written to a physicist whose name he had known for a long time because of the old 'nuclear' work of Khariton and Zel'dovich. We shall not repeat here what one can read in these reviews, but simply touch upon several historical aspects of Gamow's cosmology.

(1) The Big Bang theory is frequently also called the hot Universe theory. According to Gamow, an initial explosion occurred simultaneously throughout the Universe and filled space with hot matter from which, after thousands of millions of years, all the bodies in the Universe — the Sun, stars, galaxies, planets, including the Earth and everything on it — were formed. The key and new word in this picture is 'hot' and this applies to the matter in the Universe.



A A Friedmann, from a photograph of 1923.

The following historical comment should be made straight away. It is a surprising fact that Gamow himself thought that the idea of a hot beginning to the Universe is not his, but belongs to his teacher Friedmann. In his autobiography [1] Gamow writes: "According to Friedmann's original theory of the expanding Universe, the World begins from a 'singular state' in which the density and temperature of matter are practically infinite."

Friedmann published two papers and one popular science book on cosmology. However, nowhere does he discuss the temperature of the early Universe. Where did Gamow get this idea? A likely (and most probable) explanation is that the idea of a high temperature at a high density had been regarded in Friedmann's circle as natural or even trivial. After all, any school physics textbook says "Bodies become cooler during expansion and hotter during compression." This is in reality found to have a universal application to the whole Universe and in its literal sense.

(2) The main stimulus for Gamow's turning to cosmology has been the attempt to account for the origin of chemical elements and to determine the reasons for their relative abundance in the Universe. Gamow talked about this back in the midthirties in one of the invited lectures at Ohio University. Fortunately, this lecture was published in

Ohio in 1935, so we can say that the prehistory of Gamow's cosmology is dated and documented precisely: the idea behind the active work that started a decade later had thus already been proposed [8].

The chemical composition of the matter in stars and galaxies is surprisingly constant: it varies very little from one 'ordinary' star to another and is practically the same as in the Sun. Hydrogen represents almost three-quarters (by mass), helium accounts for about 23%, and all the other elements are present in very small amounts (a total of up to 2%). It should be mentioned that in the forties and fifties it was assumed that hydrogen and helium were present in approximately the same proportions. How did this composition arise? What is the reason for the almost universal ratio of the two main and most common elements (hydrogen and helium) in the Universe?

To answer these questions physicists and astronomers have turned to the processes in the stellar interiors, where reactions of transformation of nuclei take place, as has been known reliably since the early thirties. However, it has been found that, under typical conditions in the innermost parts of the Sun and stars, no elements heavier than helium can form in any significant amount. This was the conclusion reached in the midforties by Chandrasekhar, Bethe, and von Weizsacker.

But what if the elements have not been 'cooked' in the stars, but directly throughout the Universe in the first stages of the cosmological expansion? The universality of the chemical composition would then be ensured automatically. As far as the physical conditions in the early Universe are concerned, its matter would have undoubtedly been very dense, in any case denser than in the interiors of stars. The high density, guaranteed by Friedmann's cosmology, is the essential condition for efficient nuclear fusion reactions creating elements. A high temperature of matter is also essential for these reactions. Therefore, Gamow put forward the idea that matter in the early Universe was not only very dense, but also very hot. And this is the crux of the matter: the early Universe was, according to Gamow's idea, the 'cauldron' in which the synthesis of all the chemical elements took place at a certain density and at enormous temperatures.

(3) This treatment of the early Universe in terms of the general laws of thermodynamics and nuclear physics had proved quite unexpected for a majority of physicists and astronomers. The search for an answer to the specific questions of the real composition of the matter in space on the basis of essentially speculative cosmological theories seemed a daring and risky undertaking. Especially, as cosmology seemed at the time to be in a blind alley and gave an estimate of the age of the Universe far too low, just 2×10^9 years, whereas the age of the Sun could not have been less than $(4.5-5) \times 10^9$ years. This was related to the error in the Hubble constant determined at the time: the contradiction had been removed finally only in the late fifties. During the period we are speaking about it had been held that, as stated authoritatively by Weinberg, "it has been generally regarded that the study of the early Universe is not a task which a self-respecting scientist should spend time on" [9].

To physicists and men of Gamow's rank the generally accepted view has not been of great importance. He had been so convinced of the correctness of Friedmann's theory that he paid little attention to the discrepancies between the estimates of the age of the Universe. He approached this topic in a constructive manner: after analysis of the observational data used by astronomers to find the Hubble constant, he considered the general ideas on the stars and compared one with the other by giving preference to these general ideas. This did not mean the rejection of cosmology, but the converse: the age of the stars was used by Gamow to obtain a new estimate of the Hubble constant, which was later found to be closer to reality. The paper on the subject was published in 1953 in *Kongelige Danske Videnskabernes, Selskab, Matematisk-Fysiske Skrifter*, when the success of his cosmological ideas had already made its mark.

This work was done by Gamow together with one, then two, and then three people. These were the young scientists Ralph Alpher and Robert Herman (both from families with Russian roots) and John Follin. These young physicists were attracted by Gamow's approach to evolutionary cosmology as a worthy and noble pursuit, contrary to the current fashion in science.

(4) Gamow identified two main aspects in his cosmological theory: the synthesis of elements and the cosmic radiation. They are closely related: the synthesis of elements is possible, as mentioned earlier, only at high temperatures; however, it follows from the general laws of thermodynamics that hot matter should also contain radiation in thermal equilibrium with matter. Following the epoch of nucleosynthesis, which lasts a few minutes, radiation remains and continues to coexist with matter and to expand (as a gas of photons) together with matter in the course of the general evolution of the Universe. This radiation should be also conserved in the present epoch, but its temperature should be much lower than initially because of the considerable expansion.

This is the qualitative aspect. The quantitative solution of the problem demands explanation and prediction of specific numbers, which are the abundances of the nuclei in space and the contemporary temperature of the background (relic) radiation. Roughly speaking, a theoretician should fit in his calculation model the temperature to the density in such a way as to obtain the observed chemical composition of matter. If this can be done, then the contemporary temperature of the background radiation is calculated very easily, because cooling of the radiation from the epoch of nucleosynthesis to our epoch is described by the simple and long-known physical law of adiabatic cooling. The theory as a whole requires time-consuming and very difficult calculations: it is necessary to analyse and calculate the complex kinetics of thermonuclear transformations in transient expanding matter allowing for a whole range of circumstances and conditions, each of which can be — in principle — important and decisive for the result in question. The work took many decades and Gamow consulted such experts as Fermi and his colleague A Turkevich (Gamow mentions the latter in one of his popular science books as a physicist of Russian origin, which he notes with obvious pleasure).

(5) The first paper written by Gamow and Alpher was published in 1948 under the authorship of Alpher, Bethe, and Gamow: as reported by his students [10], Gamow mysteriously added the name of Bethe in the finished manuscript of the paper with a note 'in absentia' (which for some reason was lost in the subsequent editing). This was the origin of what became famous as the $\alpha\beta\gamma$ theory.

From a photograph in the fifties.

Gamow noted with approval that the original surname of Alpher (Il'ferovich) was in good time, i.e. a long time ago, altered appropriately and he advised Herman (former German) to change his family to, for example, Delter (in fact, he referred to Herman as Delter in one of his reviews).

In a series of papers by Gamow's group the initial theory was improved and developed from year to year, allowing in particular for the critical comments first received from the Japanese physicist Hayashi, and then from the English astrophysicists Hoyle, Fowler, E M Burbidge, and G R Burbidge. Later, the process of cosmological nucleosynthesis had been studied once more in a more rigorous manner (which became possible because of refinements that took place in nuclear physics) by Zel'dovich and his colleague V M Yakubov in 1964–1965, and simultaneously with them by Hoyle, and somewhat later by the American theoretician P J Peebles. This was accompanied by refinements of the observational astronomical data on the chemical composition of matter in the Universe.

As a result of this major collective work lasting many years and initiated by Gamow, it became obvious that (a) the cosmological abundances of the two main elements — hydrogen and helium — can indeed be accounted for by nuclear reactions in the hot matter of the early Universe; (b) the heavier elements should evidently be synthesised in a different way, for example as a result of explosions of supernovas; (c) the temperature of the background radiation during our epoch should be close to absolute zero, i.e. it should lie in the interval between 1 and 10 K.

(6) Finally, in 1965 the background electromagnetic (microwave) radiation was discovered to fill uniformly the entire cosmological space, as predicted by Gamow's theory. Its temperature was found to be 3 K. This discovery was in a sense accidental: the two American radioastronomers A Penzias and R W Wilson had never heard of Gamow's theoretical predictions and the aim of their work was in no way related to cosmology. The importance of their discovery to the fundamental science of the Universe soon became generally acknowledged.† This was the greatest observational discovery in cosmology from the time of the discovery of the general recession of the galaxies in 1929. The discovery of Penzias and Wilson radically altered the status of cosmology and the general attitude to the work of Friedmann and to Gamow's theory.

''Cosmology had become a respectable science'' was a typical saying of the midsixties. ''Who would expect that such an empty and abstract theory could lead to such important, and above all such viable astronomical consequences?'' are the words of one of the early critics of Friedmann's cosmology. ''Gamow, Alpher, and Herman deserve enormous respect, apart from anything else, because they were ready to treat seriously the early Universe and study what the physical laws should say about the first three minutes'' (this is taken from Weinberg's book [9]).

Cosmology began to grow apace. The intensive work, in which almost all the leading cosmologists and astrophysists participated, together with the young active theoreticians and observers throughout the world, rapidly led to the development of reliable, fully supported, deep cosmological concepts, confirmed by astronomical observations. Gamow's ideas were fully integrated and developed, and his name occupied rightly the same position in cosmology as that of his teacher Friedmann.

(7) The cosmological ideas of Friedmann and Gamow have survived and won in stiff competition with other cosmological theories. The success of the theory of the expanding hot Universe had been far from evident at the beginning. It has been continuously criticised, and there have been many blunders or errors, real or imaginary. The very existence of the early Universe had been doubted initially. In the midforties, British theoreticians H Bondi and T Gold, who were joined later by their colleague Hoyle mentioned earlier, put forward the theory of a steady-state Universe. This theory started from the assumption that the Universe should remain unchanged as a whole and almost the same as observed at present. The galaxies recede in this theory, as indicated by the observations, but this process is accompanied by the continuous creation of new matter, so that the average density of the Universe remains constant. This theory, put forward as a reaction to the contradictions relating to the age of the Universe in the evolution of cosmology (discussed above), suffers from a contradiction from the very beginning: the steady-state Universe has existed eternally, its size is infinite, and its future infinite. The hypothesis of the creation of matter, not supported in fact by any physical considerations (except for the argument that this is an extremely weak process which cannot be detected and cannot be rejected — even if it is not detected — by any laboratory experiments), seemed to many preferable to Gamow's ideas on the temperature and density during some unknown first minutes of the cosmological expansion process. The theory of the steady-state Universe had been a very powerful competitor to evolutionary cosmology as far as the late fifties. Later, after resolution of the conflict about the age of the Universe, this theory did not fade away but existed and fought back, demonstrating from time to time the great inventivity and

†In 1968, Penzias and Wilson were awarded the Nobel Prize. A more detailed account of the background radiation is given in a separate paper in this issue.

ingenuity of its authors. However, even the most faithful supporters of the steady-state theory laid down their arms, not without a last fight, after the discovery of the background radiation.

(8) In the mainstream of Friedmann's cosmology for several years there was a rival to the 'hot' theory of Gamow: the 'cold' theory of Zel'dovich. The starting point of Zel'dovich is the zero temperature of matter at the moment of creation of the Universe. Zel'dovich developed his theory with a characteristic broad sweep and put forward a number of thoughtful ideas on the general nature of the evolutionary process in the Universe, which still remain valid.

In 1964, Zel'dovich's colleagues A G Dorozhkevich and I D Novikov made the first detailed analysis of an observational test which could be used to support the 'cold' against the 'hot' model or vice versa. They perfectly correctly selected as the test the observation of the background electromagnetic radiation predicted by the 'hot' theory, but absent from the 'cold' theory. They precisely identified the instrument suitable for such observations: a horn aerial (antenna) described in the literature (1961), which was used later by Penzias and Wilson in their discovery. (Unfortunately, these two Moscow theoreticians were not quite accurate in the treatment of the observations already made with the aid of this aerial; they assumed that these observations gave very definite negative results and on this basis they concluded that the observations supported the 'cold' model. This misunderstanding was later clarified.)

As soon as he heard of the discovery of Penzias and Wilson, Zel'dovich immediately rejected the 'cold' model. In the autumn of 1965 he wrote to me these words: "It seems that the cold model was an error. Americans measured a radio-background. These are only rumours at present and nothing is in print." In 1966 he wrote rapidly an extensive and penetrating review [7] and presented lectures at the leading academic establishments of the Soviet Union about the theory of the hot Universe. In his fundamental monographs, written later together with Novikov, the 'cold' model is mentioned only, as he says there, by way of a self-critique.

(9) In the history of research on the background radiation there is one sad event for us. We can say that the back- ground radiation came knocking on the front door of the Pulkovo Observatory. A horn aerial operated there (very similar to that used by Penzias and Wilson) was constructed by S E Khaikin, N L Kaidanovskii, and T A Shmaonov, and this aerial recorded the background radiation back in 1956! The evidence for this is a paper by Shmaonov of 1957 [11]; nobody paid any attention to this and nobody mentioned it later in 1965. Many years later Shmaonov's paper was 'dug up' by an American (!) historian of science.

(10) Gamow regarded as essential parts of his cosmological theory not only the primordial nucleosynthesis and the background radiation, but also the cosmogony of galaxies. The problem of the creation of galaxies attracted Gamow back in 1939; at the time he and Teller attempted to develop for this purpose a theory of gravitational instability in the expanding hot matter of the Universe. Later, in 1946, this was solved fully (in the linear approximation) by E M Lifshitz. The theory of gravitational instability, in the nonlinear variant, was developed further by Zel'dovich and his colleagues.

In the early fifties Gamow became interested in one other more specific problem in cosmology: why galaxies rotate. He postulated that their rotation is related to a vortex-like turbulent state of the medium from which they were created. This idea has also been developed in modern cosmology. It has been found that the vorticity appears at the later nonlinear stage of the gravitational instability when large-scale supersonic flows appear in the cosmological medium and they are accompanied by discontinuities in the velocity and density of matter. In principle, these vortices are capable of imparting rapid rotation to galaxies formed from such matter [12].

It is remarkable that one of the most constructive aspects of the study of the cosmogony throughout the Universe is the observation of the background radiation, because it carries information on the earlier pregalactic history of the Universe. The initial small deviations from general uniformity in the distribution of matter, which stimulated the development of gravitational instability, have left their traces in the angular distribution of the background radiation. The search for such 'footprints in the sky' of the pregalactic structure of the Universe has been successful: these footprints were discovered directly in 1992 by American investigators who used apparatus on board the special COBE satellite, and also by a Moscow group of astrophysicists at the Institute of Space Research of the Russian Academy of Sciences with the aid of the 'Relikt' orbiting instrument.

I shall conclude this 'cosmological' section by mentioning a letter from Einstein to Gamow dated 1948. It has been preserved and published in the Gamow memorial volume edited by F Reines [13]. Einstein thanks Gamow for the manuscript of Gamow's first paper on the theory of the hot Universe and supports the motivation as well as the initial physical assumptions. He says that in view of his lack of particular knowledge he cannot deal with the problem of formation of galaxies. A published photocopy of the letter clearly reveals Gamow's note: "Of course, the old man agrees with almost everything nowadays. Geo." Gamow did not mention how sharp the first reaction of Einstein was to the evolutionary cosmology in Friedmann's paper a quarter of a century earlier.

7. The alphabet of life

In 1938 Vernadskii wrote a paper on "Study of life and new physics"†. Thirteen years later, in 1944, one of the founders of quantum mechanics, Erwin Schrodinger, published the book *What is Life? The Physical Aspect of the Living Cell* (the Russian translation was published in 1948 by Inostrannaya Literatura in Moscow). The fundamental problems of life, considered as complex physical phenomena, have become one of the most topical subjects in biology and in science in general. Can we regard as unexpected or accidental that Gamow was attracted to these problems? He could hardly stand apart from the branch of science where a critical breakthrough, a new major step, had obviously been approaching. Gamow felt strongly that decisive steps would be made very soon in genetics. He therefore tackled the genetic code.

† Issue No. 3 in *Izvestiya Akademii Nauk SSSR,* Series VII (1931) p. 1. Approximately at the same time Vernadskii proposed election of Gamow to the Academy of Sciences of the USSR.

The problem of the molecular genetic code, i.e. a system for storing genetic information in macromolecules of living organic matter, was already clearly defined in Schrodinger's book. However, its solution became possible only later, when it had been established that genetic information is stored in a coded form by molecular chains of nucleic acids. In 1953 the British crystallographer F Crick and the American biochemist J Watson determined the structure of deoxyribonucleic acid (DNA) as a system of two complementary, i.e. mutually fitting, helices composed of nucleotides. It became clear that the genetic text is written in the form of consecutive linear words and sentences in which four nucleotide 'bases' serve as the alphabet. In the case of DNA these four 'letters' are adenine, guanine, cytosine, and thymine (in ribonucleic acid, RNA, the place of thymine is taken by uracil).

As soon as the composition and genetic function of the DNA were revealed, Gamow joined the others and soon, in 1954, could formulate for the first time in science the specific and precise task of deciphering the genetic code.

Gamow started from the following general assumptions. Proteins are the building bricks of all that lives: living tissues are formed from them, and so are hormones, enzymes, etc. In the human organism there are over a million different proteins. Proteins are constructed from twenty amino acids. The individual properties of a protein are determined by the constituent amino acids and these acids store and transmit complete information on the protein structure. The method of storing this information with a four-letter alphabet is universal and the same for all living matter on Earth: animals, plants, bacteria, and viruses. Each 'word' in the genetic text is the name of the amino acid; each 'sentence' defines a protein.

If the alphabet of life consists of four letters, then how are the words constructed? This was the question Gamow asked in 1954.

Obviously, the number of words should not be less than twenty. If we assume that each word consists of two letters, then the number of different pairs is $4^2 = 16$. This is too small. Gamow postulated that each word should most probably be three letters. The number of such three-letter words in the four-letter alphabet should be $4^3 = 64$. This is now much greater than the number of amino acids.

What is the answer? It could be that the words need not consist of three letters each. Alternatively, there could be synonyms among the 64 three-letter words. Gamow considered the latter alternative as the simpler: let us assume that there are 64 words but that some of them represent the same amino acid.

The correspondence between the 64 words of the language of life and 20 amino acids ought to be determined experimentally. Further purely combinatory considerations would be far too risky and would represent piling guess upon guess. However, the best theoretical minds of the West had been drawn into this contagious and hazardous game.† Richard Feynman, one of the founders of quantum electrodynamics proposed his own method for deciphering the language of life. Teller was not left behind. Even Gamow succumbed to the temptation to try his luck and complete the solution of the problem by purely theoretical means. His variant was the simplest and most elegant [14]:

"Let us assume that we are playing 'simplified poker' in which each player has a hand of just three cards and the whole pack consists solely of aces belonging to four suits. How many different combinations of cards can a player receive? First, he will receive one of the four sets of three aces of the same suit: three hearts, three diamonds, three clubs, and three spades. Next, he can get pairs of identical cards in each set of three, for example: two hearts and a diamond, two diamonds and a club, and so on. The total of such combinations is just twelve. Finally, there are variants with three different suits; in this case there are four different combinations. Thus, a hypothetical player can have one out of 20 possible sets of three cards, which is exactly equal to the number of different amino acids forming long protein molecules." This gives 20 'meanings' of 64 words, where the order of letters is unimportant.

New experiments of Crick, as well as the work of American biochemists M Nirenberg, S Ochoa, and H G Khorana and others, soon demonstrated that Gamow's idea of a universal code with three-letter words is absolutely correct. This was a triumph for genetics and at the same time an enormous personal success for Gamow. He celebrated his victory and we know that he could celebrate very well.

As far as the synonyms are concerned, the rules by which different words assume the same meaning had not been guessed by anybody then: they proved quite intricate, but not at all like those in the 'simplified poker'. It is now known that out of 64 words there are 61 that code for amino acids; the remaining 3 words code for the completion of sentences: they are the stops that end the sentences.

In the interview which I mentioned at the very beginning of the paper Gamow says that perhaps the genetic code was his greatest achievement. He also recalls that the biologists were initially hostile to his work: he was unable to publish even the first note on the subject in the USA and had to send it to Denmark to be published in *Biologiske Meddelelser Kongelige Danske Videnskabernes Selskab* **22** No. 8 (1955), because he was a member of the Danish Academy of Sciences. It is pleasant to note that one of Gamow's papers on the code was published (by oversight?) in the Soviet Union [15]. This was the first time this happened since 1933.

8. The Gamow Tower

In the spring of 1968 in his house in Boulder, Colorado (this house he himself and all others called Gamow's dacha), Gamow answered questions from C Weiner, a historian of science. The meeting went on for a long time, several hours one day and then Gamow talked and talked the next day. Gamow was then seriously ill, he had several vascular operations in the preceding six months, caught and went through hepatitis in hospital. However, Weiner noted that he was cheerful, happy, and witty (this can be readily confirmed by the transcript of the taped interview, preserved at the American Institute of Physics in New York); he even sang bits of an opera in honour of Bohr, which he wrote and performed some time in the past with his friends.

At this interview, which proved to be his last, Gamow identified his most important achievements. The list is given

† That period was far from the most propitious for genetics in the Soviet Union.

Congress of physicists in Poland ('Cracow Days') June 1938. First row from left to right: G A Gamow (second) and L Rosenfeld (fourth). Second row: second and third from left Niels Bohr and his wife. Third row: second from left, Charles Darwin Jr. This Congress wasremembered above all by Gamow because of a talk by Charles Darwin (grandson of the famous Charles Darwin), from whose introduction began the exceptionally successful career of Gamow as a science populariser. (This photograph was kindly supplied by V Ya Frenkel'.)

at the beginning of my paper. Following this list, I describe those achievements that pertain to the American period of his life. This description is not even-handed: effectively nothing is known on Gamow's work on the hydrogen bomb and my account goes round the topic (we simply know very little about this work), but I give most detail about the Big Bang because many regard this as Gamow's greatest contribution to twentieth-century science (one could say much more about this, but for the limitations of this paper).

Unfortunately, other important scientific results of Gamow are outside the scope of my paper and even a list will not be attempted. However, in order to partly fill the gap I shall simply name three of them:

(1) the Gamow–Teller resonance, which is the effect in nuclear physics discovered theoretically in 1936 and given new life much more recently by Bethe and many others;

(2) URCA process (1941), which is important in both nuclear physics and its applications in astrophysics, for example, in the explanation of the mechanism of outbursts of supernovas; to help his serious colleagues, he suggested the following interpretation of the name: unrecordable cooling agent (by which he meant a neutrino);

(3) key relationships governing the evolutionary paths of stars in the spectrum–luminosity diagram (1938–1957).

The three achievements of the highest rank are alpha decay, the Big Bang, and genetic codes. The three lesser results are those just listed. Such an expansion in triplets could probably be continued. Gamow himself used a three-term formula not so much in the case of scientific results, but about his income. He said that (as in one highly regarded science) there are three sources and three constituent parts of his money: teaching, scientific consultation, and popular science books and papers.

The last gave most money and fame. His book — and he wrote over 20! — and particularly the series on the experiences of Mr Tompkins, have had tens of editions in all European and many non-European languages. However, the Russian language has been the exception. In 1994 'Tompkins' appeared at last in the native language of his author in the 'Kvant' Library series. Gamow's work as a populariser was rewarded in 1956 by the very generous and respected UNESCO Prize. This enabled Gamow to travel to India and Japan, which he had dreamt of for a long time.

Much can be said about this third component of his activities. However, I shall make just one comment. His popular papers and books were read not only by 'inquisitive pedestrians' (intelligent laymen). Sakharov in Arzamas read Gamow in *Scientific American* and Gamow's popular paper of 1956 on the genetic code stimulated Sakharov's thinking on the genetic consequences of nuclear tests and led to Sakharov speaking out in public [16].

L E Gurevich said that a theoretician can be superior or inferior to his work. Gamow most probably was equal to his work. He managed to do much, in some cases he was slightly lazy, sometimes he was lucky, and sometimes he 'yawned' (in the case of the charge independence of the nuclear forces; this followed from 1935 experiments well known to Gamow, which were carried out on Tuve's accelerator at the Carnegie Institute, where Gamow was an unpaid consultant). That spring of 1968 he told Weiner at his dacha that it seems that he wrote about everything that he knew; Gamow added that perhaps the only thing he might still do is to write a cookbook.

His work and his character as a physicist and as a man is reflected in his papers and books. Very early, from the late twenties, beginning with the stanzas written about him by Dem'yan Bednyi in *Pravda*, a legend arose about Gamow. In the Soviet Union it grew and evolved, changing as times became hard or less hard. The legend has its own separate life in the West, following the Western mythology. It has not yet been collected in one place and exists in the form of facts and nonfacts of different styles, and also as brief stories. I shall end with a list of these, which is not in any particular order:

— one of the well-known trinity: Kham – Khamov – Khameleon (Landau – Gamow – Bronstein);

— he ran away to the West, because by then he was completely drained of ideas and in the West he made no significant contribution;

— he was not a very good man: he went away, leaving behind his blind father;† he misled Abram Fedorovich (Ioffe) to vouch for him and since then no physicists were allowed to go abroad;

— an unhappy alcoholic, he died alone, far from the country of his birth, without friends or students;

— he helped the Soviet intelligence to obtain the most important information on the American atomic bomb (this is stated in a very recent book by a KGB general, published in the USA, who listed among the invisible front-line soldiers not only Gamow, but also Bohr, Fermi, Oppenheimer, and Szilard; he failed to include only Teller and Bethe from among the most important Los Alamos scientists because they are very much alive and anyway would know what to do with the general and his publishers);

— he loved life, liked the hazard of theoretical guesswork, was inexhaustible in his inventiveness in science, jokes, and pranks;

— he was the patriarch of modern astrophysical theory;

— he was a man of inexhaustible energy and humour who graced any company with his joy, an inexhaustible store of anecdotes and penetrating physics questions and riddles;

— physics was a pleasure for him and he worshipped physics to a degree rarely encountered and, moreover, was capable of imparting this feeling of delight and inspiration in his books and lectures, addressed both to scientists and all those interested in science;

— Gamow's mind travelled freely over large areas of physics and biology;

— all his papers in *Physical Review* were printed in the issues published on 1 April (a gross exaggeration, only 11 such cases have been found);

— he was a blond of 1.9 metres in height (the exact figure was 6 feet and 4 inches);

† Gamow's father, Anton Mikhailovich, was not blind, although his sight deteriorated with age. He lived in Odessa and received from his son ''many food and clothing parcels'', as established recently by the historian Lisnevskii [17]. In the last years of his life Gamow's father was very afraid that ''they will come to get him''; he committed suicide in 1938.

— he loved meals with friends (for example, a bottle of whisky consumed solo during an evening with Lovell at Joddrell Bank);

— he was an extravagant Russian extrovert;

— brilliant but not sound (this old Russian saying was repeated in many languages about his talents);

— good theoreticians see analogies between ideas and the best see analogies between analogies, like Gamow;

— he was out of this world.

The last is the title of a paper on encounters with Gamow, written by a man who knew him for 40 years, Nobel Prize laureate Max Delbruck [13]; let us close the legend with these words.

The American half of Gamow's life can be divided into three periods: Washington, Los Alamos, and Colorado (the second is not so much a geographical label as one expressing the function). In the middle fifties there were changes in his personal life (divorce from Lyubov' Vokhmintseva, marriage to Barbara Perkins), which induced a wish to change location, frequent in such cases. As a result, in 1956 Gamow went to Boulder. He remained professor at the University of Colorado until his death on 20 August 1968. He was then 64 years old.

He built a house, Gamow's dacha, to his own taste in Colorado. The University built on its campus a high building known as the Gamow Tower. Gamow's son, Rustem-Igor Gamow, is working at the University of Colorado; he was born in 1935 in Washington. He is a well-known biophysics professor and master mountaineer. Following all the rules of biophysics, he invented a sleeping bag; it is said that one can sleep well in it on any glacier. It is called Gamow's bag.

Acknowledgements. I am obliged to Professor S Weart for an opportunity to become acquainted with the Gamow materials (text, tape recordings) stored at the History of Physics Center of the American Institute of Physics in New York. For meetings and letters, from which I learned much about Gamow, I am grateful to Professors R A Alpher, R Herman, B Lovell, A Bartlett, and P O Lindblad, who worked with Gamow or met him. I am indebted to Professors M Valtonen and S Mikkola for the hospitality at the Tuorla Observatory, where this paper was written.

References

1. Gamow G *My World Line: an Informal Autobiography* (New York: Viking Press, 1970)
2. Rubin V in *Gamow Cosmology* (*Proceedings of the International School of Physics 'Enrico Fermi', Course 86, Villa Monastero, Varenna, Italy, July 1983*, Eds F Melchiorri, R Ruffini) (Amsterdam: North-Holland, 1987) p. 160
3. Blumberg A, Panos L G *Edward Teller: Giant of the Golden Age of Physics* (New York: Scribner, 1990)
4. Smyth H D *Rev. Mod. Phys.* **17** 351 (1945)
5. Clark R W *Einstein: The Life and Times* (Introduction by Bernard Lovell) (London: Hodder and Stoughton, 1982)
6. Bronshtein [Bronstein] M P *Usp. Fiz. Nauk* **11** 124 (1931)
7. Zel'dovich Ya B *Usp. Fiz. Nauk* **86** 303 (1965) [*Sov. Phys. Usp.* **8** 489 (1965)]
8. Gamow G *Ohio J. Sci.* **35** (5) 1935)
9. Weinberg S *The First Three Minutes* (New York: Basic Books, 1977)
10. Alpher R, Herman R *Phys. Today* **41** (8) 24 (1988)
11. Shmaonov T A *Prib. Tekh. Eksp.* (1) 86 (1957)
12. Chernin A D *Astron. Astrophys.* **267** 315 (1993)

13. Reines F (Ed.) *Cosmology, Fusion and Other Matters: Gamow Memorial Volume* (Boulder, CO: Colorado Associated University Press, 1972)
14. Gamow G *Matter, Earth, and Sky* (Englewood Cliffs, NJ: Prentice-Hall, 1965)
15. Gamow G in *Voprosy Biofiziki* (Problems in Biophysics) Moscow: Inostr. Lit. 1957) p. 203
16. Sakharov A D *Znamya* (12) (1990)
17. Lisnevskii Yu I *Vopr. Istor. Estestvozn. Tekh.* (1) 48 (1989); (2) 97 (1989)