Nuclear fusion in the sun

The radiant energy of the sun is the driving mechanism for many natural processes on earth. It provides the energy for plants and living beings and determines the climate. The sun releases a radiation power of $3.85 \cdot 10^{26}$ W (joules per second). This corresponds per second to roughly 10^6 times the annual world energy consumption (2004)! Where does the sun get this energy from?
At the end of the 1930s, it was discovered, through astronomic spectroscopy, that nuclear reactions are occurring in the interior of glowing stars, including our sun, and that these are the motor behind its luminosity. Since spectroscopic examinations of the sun have shown that hydrogen is the main element here, the obvious conclusion was that it probably played a decisive part in this. The decisive work on the nuclear reaction in the sun was provided in 1939 by Hans Bethe; he was awarded the Nobel Prize for his work as a whole in 1967.

How does the “motor” of the sun work?

The sun is not solid – it is a ball of gas. The core of the sun (which accounts for around 25 % of the total diameter of the sun and 50 % of the solar mass) essentially consists of hydrogen (^1H).

Conditions required for nuclear fusion

The temperature at the core of the sun is approx.10 – 15 mill. K.
The result of this is that the hydrogen is present in completely ionized form as “plasma”: the nuclei and electrons are separated. The sun therefore consists of a cloud of electrons and protons. At the same time, because of the extremely high gravitational forces, this plasma is held together by a pressure of more than 200 billion bar. This is an unimaginably high pressure! It is about 200 billion times more than the earth's atmosphere.

Hydrogen becomes helium

In our sun, the “proton-proton cycle” takes place, in which hydrogen nuclei fuse to helium nuclei. This reaction can only take place at an extremely high temperature and under extremely high pressure, since the kinetic energy of the atomic nuclei must be sufficient to overcome the Coulomb repulsion effect. This process is supported by the quantum mechanical “tunnel effect” – without this, much higher temperatures would be needed for nuclear fusion. A helium nucleus created during fusion weighs less than its components (two neutrons and two protons) together. During fusion, a portion of radiant and thermal energy corresponding to this difference in mass occurs ($E = m \cdot c^2$). Because of the mass deficit of the helium fusion process, 0.7 % of the sun's mass can be emitted over time.
The fusion of hydrogen to helium can take place through various processes. The most important chain of reactions consists of the following three steps:

$$^1H^+ + {}^1H^+ \rightarrow {}^2H^+ + e^+ + \nu_e + 0.42\ \text{MeV}^* \quad (1)$$

$$^2H^+ + {}^1H^+ \rightarrow {}^3He^{2+} + \gamma + 5.49\ \text{MeV} \quad (2)$$

$$^3He^{2+} + {}^3He^{2+} \rightarrow {}^4He^{2+} + {}^1H^+ + {}^1H^+ + 12.86\ \text{MeV} \quad (3)$$

* The positron disintegrates when it meets an electron and releases energy: $e^+ + e^- \rightarrow 2\gamma +$ 1.022 MeV. The neutrino generally leaves the sun without any further reactions, and its energy (0.26 MeV) can no longer be used.

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In total, in the formation of a helium nucleus, almost 27 MeV are released – in the form of kinetic energy, neutrinos and electromagnetic radiation (for example gamma radiation, heat radiation, visible light, etc.). (Remember that four hydrogen nuclei are needed to create one helium nucleus ^{4}He: The fusion reactions (1) and (2) each have to run twice so that two ^{3}He nuclei are produced, which can then fuse to ^{4}He.)
The radiation power of the sun of $3.7 \cdot 10^{26}$ W results from the combustion of 570 mill. t of hydrogen to 566 mill. t of helium – so the mass of the sun is decreasing by 4 mill. t a second.

How does the energy reach the surface of the sun?

The energy from the nuclear fusion is released in the interior of the sun and has to reach the surface before it can be emitted into space. The photons (energy quantums) that are released in nuclear fusion collide with the plasma and the gas particles in the gaseous layers of the sun, which is why they do not reach space directly from the interior, but diffuse to the surface from the sun's interior outwards. They take several million years to do this. So the light that we see today was created a very long time ago.
By the way: Only a decreasingly small proportion of the radiation from the sun falls onto the earth. The average radiation power reaching the earth is 1.37 kW/m^2 (solar constant). If we considered the fact that, at the moment, only 0.1 % of this is used by photosynthesis and that today, people are using almost none of it, this radiant energy represents an inexhaustible stock of energy!

What if the fuel for the sun's “motor” starts to run short?

The sun came into existence around 4.6 billion years ago. A simple estimate shows that, with the hydrogen still present in its inner core, the sun will keep on shining for a further 100 billion years or so:

Mass of the sun: $1\text{-}99 \cdot 10^{30}$ kg,
Mass deficit: 0.7 %,
Radiation power P: $3.85 \cdot 10^{26}$ W,
Speed of light c: $2.99 \cdot 10^{8}$ m/s

Radiated energy $E = 0.007 \cdot (1.99 \cdot 10^{30}\ \text{kg}) \cdot c^2 = 1.25 \cdot 10^{45}$ J

Lifetime $t_{Sun} = E / P = 1.25 \cdot 10^{45}\ \text{Ws} / 3.85 \cdot 10^{26}\ \text{W}$
$= 3.25 \cdot 10^{18}\text{s} \approx 10^{11}$ a

The value is approx. 20 times greater than the current age of the sun!

More complex calculations (for example by the Max Planck Institute for Plasma Physics), on the other hand, give a remaining combustion duration of approx. 5 billion years. And fusion will not end as stocks of hydrogen run low either. The decreasing gas pressure causes the sun's core to contract, making it hotter. “Helium combustion” (fusion of helium nuclei) starts. The remaining hydrogen migrates outward and a second combustion zone appears. The outer layers of the sun expand as a result – and the sun becomes a “red giant”. After the helium fusion, the sun no longer has sufficient energy reserves to pass to the next fusion stage – that of carbon. The outer layers collapse and become colder, creating a “white dwarf”.

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Synthetic sun in the power plant

Since the middle of the 20th century, researchers have been working on imitating the nuclear fusion of the sun in a reactor. This would ensure our energy supplies for ever, since hydrogen as a fuel in nuclear fusion (the proton-proton cycle) has a calorific value of $629 \cdot 10^6$ MJ/kg. (For comparison: calorific value of the nuclear fuel ^{235}U in nuclear fission $89.9 \cdot 10^6$ MJ/kg, calorific value of fossil fuels 30 MJ/kg.)
Unfortunately, it's not that easy. In the first place, you need elementary hydrogen. But hydrogen is only available on earth in compound form, for example in H_2O! Consequently, energy has to be used first, to produce the hydrogen, for example from the electrolysis of water. This is not a problem in terms of energy, since the amount used is negligible in comparison with the energy obtained from fusion.
The real difficulty lies in reproducing the extremely high temperature and extremely high pressure that prevail in the interior of the sun in order to create plasma of the necessary density. Only then can a chain reaction start that will provide enough energy to keep going on its own and also release surplus energy. But all attempts so far have only been able to maintain the chain reaction for a few seconds. In order to lower the high initial energy requirement and to be able to better remove the surplus energy, the example of the sun has been dropped; instead, the hydrogen isotopes deuterium (D = ^2H) and tritium (T = ^3H) are used as the fusion partners:

$$D^+ + T^+ \rightarrow {}^4He + {}^1n + 17.6\ \text{MeV}$$

Here, other reaction products are also produced which are of crucial technical significance: The neutron that is released is braked in the reactor casing and heats it up – in this way, heat is therefore transported out of the fusion zone! This heat is taken off via heat exchangers and used to generate steam which drives a turbine and thus a generator for the generation of electric power.
The calorific value in the nuclear fusion of D and T is $414 \cdot 10^6$ MJ/kg (mass deficit 0.46 %). In this way, with less than 1 g of this fuel, it would be possible to generate the same energy as is produced in a thermal power station through the combustion of 10 t of coal or oil.
Note: It is not only the technical realization of the fusion that is a problem, but also its waste: tritium is a radioactive fuel and the reactor walls are irradiated by the neutrons and age quickly. However, the quantity of radioactive waste is extremely low in comparison with nuclear fission and their half-life is relatively short.

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