The Case of Missing Solar Neutrinos with their Split Personalities

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Introduction

The Sun has played a significant role in the development of physics and mathematics over the past few centuries. Thus, Kepler's laws provided the framework for describing motions of planets under the influence of Sun's gravitational field and laid the foundation for the Newtonian theory of gravitation that successfully expounded the mechanics of planetary motions and the precession of their elliptical orbits.

Indeed, measurements were refined by the end of the nineteenth century to such an extent that the unaccounted precession of the orbit of planet Mercury was observed to be close to 43 seconds of arc per century. The excellent agreement between the prediction of the general theory of relativity and the observed precession of the perihelion of Mercury was a great triumph for Einstein's geometrised formulation of gravitation. Another remarkable prediction of general relativity was the gravitational deflection of light rays from a background star grazing the solar limb. It was measured to a reasonable amount of accuracy during the total solar eclipse expedition of 1919 and was demonstrated to be approximately twice the Newtonian value, close to the predicted value of 1.75 arc seconds. It is clear the Sun has played a major role in verification of general relativity and contributed to its widespread acceptance.

Sun has been widely regarded as the 'Rosetta Stone' of astronomy. This is undoubtedly an apt description since its internal and external layers have provided a readymade laboratory for testing atomic and nuclear physics, high-temperature plasma physics and magne-

Importance of solar observations.

tohydrodynamics, neutrino physics and general relativity. The proximity of our star has enabled us to make a close enough scrutiny of its surface and the overlying atmosphere and has provided a wealth of information, of high spatial resolution, about its surface features which is clearly not possible for other stars situated too far away from us. More than a century ago all that was known about the Sun was from the study of its face and the visible layers. Indeed, the early astronomers had not failed to notice dark blotches on the surface of the otherwise immaculate solar body. These spots were known to the Chinese and Greek astronomers, but it was Galileo who first made scientific observations of the march of these dark regions across the solar disk. Solar astronomers have kept systematic records of the appearance and disappearance of these striking features on the visible disk, hoping to gain an insight into the processes that drive the solar cycle as well as to link solar activity with terrestrial climatic changes.

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The atmospheric layers of the Sun display a rich variety of features and complex phenomena which can be witnessed in their awesome splendour during the occurrence of a total solar eclipse. Thus, the chromosphere appears fleetingly just before and after totality as a firey red ring around the disk and lingers for seconds before disappearing. Then comes into view the extremely hot, inhomogeneously structured corona which changes its shape synchronously with the activity cycle, forming a jagged ring around the Sun at the peak of solar activity and transforming into trailing plumes and streamers by the end of the cycle.

Solar Structure

The early investigations in solar physics were largely concerned with an extensive collection of spectroscopic data for studying the surface temperature and chemical composition. The spectroscopy of the solar surface revealed the presence of a host of spectral lines of elements such as carbon, silicon, sodium, iron, magnesium etc. In fact, helium was first discovered on the Sun before it was known in the laboratory. It was the spectroscopy of the chromosphere during a total solar eclipse which established that hydrogen is the most abundant element in the Sun, with helium being the next. With this knowledge of the surface chemical composition, solar physicists turned their attention to understanding its internal structure.

Early work on the structure of the Sun.

It was widely believed for several centuries that the interior of the Sun and stars shielded by the material beneath the visible surface will never be directly accessible; this prompted the nineteenth century French philosopher, Augste Comte to proclaim: "We can never learn their internal constitution" It is, therefore, a triumph of theory of stellar structure that we have been able to construct a reasonable picture of the Sun's interior with the help of a set of mathematical equations governing its mechanical and thermal equilibrium (*Box* 1)maintained by nuclear energy generation in the central regions (*Box* 2), together with the boundary conditions provided by observations. The landmark contributions by pioneers like Lane, Emden, Eddington, Chandrasekhar, the Schwarzschilds, Hoyle, Bethe and Salpeter amongst others have enabled us to construct theoretical models for inferring the physical conditions inside the Sun. The outstanding question was how to check the correctness of these theoretically computed models and how to test the underlying premise that the Sun shines because hydrogen is converted into helium in its deep interior. In the early development of this field, a picture of the solar interior was inferred basically by studying simple models and later studies were based on the numerical integration of structure equations using high-speed computers, with the auxiliary input of physics supplemented by appropriate boundary conditions.

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Box 1. Stellar Structure in a Nutshell

The central problem of solar structure is to determine the march of thermodynamic quantities with depth using equations governing mechanical and thermal equilibrium. The mechanical equilibrium ensures that the pressure gradient balances the gravitational forces.

$$\frac{dP(r)}{dr} = -\frac{Gm(r)}{r^2}\rho(r),$$

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r).$$

Here $P(r)$ is the pressure, $\rho(r)$ the density and $m(r)$, the mass interior to the radius, r, for a spherically symmetric Sun.

For maintaining thermal equilibrium, the energy radiated by the Sun, as measured by its luminosity, must be balanced by the nuclear energy generated throughout the solar interior,

$$\frac{dL(r)}{dr} = 4\pi r^2 \rho(r)\epsilon,$$

where ϵ is the energy generation rate per unit mass and $L(r) = 4\pi r^2(F_{\text{rad}} + F_{\text{conv}})$ is the luminosity. Here F_{rad} and F_{conv} are respectively, the radiative and convective flux of energy. The energy generation takes place in the central regions by thermonuclear reactions converting hydrogen into helium mainly by the proton-proton chain which contributes 98% to the energy production with an additional contribution of less than 2% from the carbon-nitrogen-oxygen(CNO) cycle reaction (see *Box* 2).

The energy generated by these reaction networks is transported from the centre to the solar surface where it is radiated into the outside space. In the inner two-thirds of the solar interior the energy is carried by radiative processes and the flux of radiation, F_{rad} is related to the temperature gradient by,

$$F_{\text{rad}} = -\frac{4acT^3}{3\kappa\rho}\frac{dT}{dr}.$$

Here a is the Stefan–Boltzmann constant, c the speed of light and κ the opacity of solar material. In the zone extending approximately one third of the solar radius below the surface, the radiative temperature gradient becomes unstable to convection. The convective flux modelled in the framework of a local mixing-length formulation is expressed as

$$F_{\text{conv}} = -\kappa_t \rho \frac{dS}{dr}.$$

Here κ_t is the turbulent diffusivity and S, the entropy.

Box 2

Proton-proton chain

$$
\begin{array}{lrl}
 & p + p \to d + e^+ + \nu_e & (\leq 0.42 \text{ MeV}) \\
 & p + e^- + p \to d + \nu_e & (1.44 \text{ MeV}) \\
 & p + d \to {}^3\text{He} + \gamma & \\
\text{pp-I}: & {}^3\text{He} + {}^3\text{He} \to {}^4\text{He} + 2p & \\
 & {}^3\text{He} + p \to {}^4\text{He} + e^+ + \nu_e & (\leq 18.8 \text{ MeV}) \\
\text{pp-II}: & {}^3\text{He} + {}^4\text{He} \to {}^7\text{Be} + \gamma & \\
 & {}^7\text{Be} + e^- \to {}^7\text{Li} + \nu_e & (0.38, 0.86 \text{ MeV}) \\
 & {}^7\text{Li} + p \to {}^8\text{Be} + \gamma & \\
 & {}^8\text{Be} \to 2\,{}^4\text{He} & \\
\text{pp-III}: & {}^3\text{He} + {}^4\text{He} \to {}^7\text{Be} + \gamma & \\
 & {}^7\text{Be} + p \to {}^8\text{B} + \gamma & \\
 & {}^8\text{B} \to {}^8\text{Be} + e^+ + \nu_e & (\leq 14.6 \text{ MeV}) \\
 & {}^8\text{Be} \to 2\,{}^4\text{He} &
\end{array}
$$

Carbon-nitrogen-oxygen cycle

$$
\begin{array}{rcll}
{}^{12}\text{C} + p & \to & {}^{13}\text{N} + \gamma & \\
{}^{13}\text{N} & \to & {}^{13}\text{C} + e^+ + \nu_e & (\leq 1.2 \text{ MeV}) \\
{}^{13}\text{C} + p & \to & {}^{14}\text{N} + \gamma & \\
{}^{14}\text{N} + p & \to & {}^{15}\text{O} + \gamma & \\
{}^{15}\text{O} & \to & {}^{15}\text{N} + e^+ + \nu_e & (\leq 1.7 \text{ MeV}) \\
{}^{15}\text{N} + p & \to & {}^{12}\text{C} + {}^4\text{He} & \\
 & \text{or} & & \\
{}^{15}\text{O} + p & \to & {}^{16}\text{O} + \gamma & \\
{}^{16}\text{O} + p & \to & {}^{17}\text{F} + \gamma & \\
{}^{17}\text{F} & \to & {}^{17}\text{O} + e^+ + \nu_e & (\leq 1.7 \text{ MeV}) \\
{}^{17}\text{O} + p & \to & {}^{14}\text{N} + {}^4\text{He} &
\end{array}
$$

From these extensive studies a standard solar model (SSM) has emerged based on a minimum number of assumptions and physical processes, which has proved to be very handy. In the SSM the Sun is assumed to be a spherically symmetric object with negligible influence

Generation and transport of energy in the Sun.

of rotation, magnetic fields, mass loss or tidal forces on its global equilibrium structure. It is supposed to be in a quasi-stationary state maintaining mechanical and thermal equilibrium. The thermonuclear energy generation takes place in the solar core by nuclear reactions which convert hydrogen into helium mainly by the proton-proton chain and to a much lesser extent by the carbon-nitrogen-oxygen cycle. The reaction network releases electron neutrinos which interact very weakly with matter. The energy is transported outward from the central regions principally by radiative processes but in the outer one third of the solar radius below the surface, the energy flux is carried largely by convection. There is supposed to be no mixing of nuclear reaction products outside the turbulent convection zone, except for the gentle gravitational settling of helium and heavy elements by diffusion beneath the convection zone into the radiative interior. It is assumed that there is no other mode of energy transport (e.g., wave motion) operating inside the Sun and the standard nuclear and neutrino physics is adopted for constructing theoretical solar models to obtain the present solar luminosity and radius using a couple of adjustable parameters. It turns out the solar interior is transparent to neutrinos released in the energy generating core and also to seismic waves generated through the bulk of the solar body. These serve as complementary probes which furnish valuable tools to have a real 'time' look into the Sun.

Probing the Solar Central Region

Historically, the measurement of neutrinos produced in the reaction network operating in the central regions of the Sun was the first probe designed to surmise the physical conditions in the deep interior. Neutrinos are elusive sub-atomic particles that interact extremely weakly with matter and travel essentially at the speed of light. They have no electrical charge and come in three types:

electron-, muon- and tau-neutrinos. The neutrino fluxes are highly sensitive to the temperature and composition profiles in the central regions of the Sun. It was, therefore hoped that the steep temperature dependence of some of the nuclear reaction rates involved would enable a determination of the Sun's central temperature to an accuracy of better than a few percent. The motivation for setting up experiments to measure solar neutrino fluxes was "to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars" In fact, John Bahcall declared in 1967 that "the use of a radically different observational probe may reveal wholly unexpected phenomena; perhaps, there is some great surprise in store for us when the first experiment in neutrino astronomy is completed" There have been valiant efforts undertaken over the past 40 years to set up experiments designed for the exceedingly difficult measurement of neutrinos from the Sun. Raymond Davis's Chlorine experimental set-up located some 1480 m underground in the Homestake gold mine in South Dakota has been operating since the mid-1960s. It has a tank containing 615 tons of liquid perchloroethylene and is sensitive to intermediate and high energy neutrinos. In this experiment the chlorine nuclei serve as solar neutrino absorber according to the reaction.

The solar neutrino puzzle.

$$^{37}\mathrm{Cl} + \nu_{\odot} \rightarrow ^{37}\mathrm{Ar} + e^{-} \quad (\text{threshold} = 0.814\ \text{MeV})$$

The capture rate is dominated by the high-energy ^{8}B neutrinos contributing 5.9 SNU, with the ^{7}Be neutrinos making a contribution of 1.1 SNU (1 SNU = 10^{-36} captures per target atom per second). Right from the beginning, Davis has been reporting measurements of the solar neutrino capture rate which have been consistently lower than that predicted by the standard solar model. The latest Homestake measurements report the solar counting rate of 2.56 ± 0.23 SNU which are at variance with the counting rate of 7.6 ± 1.2 SNU calculated with theoretical models. This puzzling deficit in the neutrino counting rate, by nearly a factor of 3 over the SSM prediction, constitutes the solar neutrino problem which has been haunting the community for over three decades. We have displayed in the accompanying figure the energy spectrum of neutrino fluxes from each of the 8 nuclear reactions that produce neutrinos in the standard solar model, along with the energy threshold of currently operating neutrino detectors (*Figure* 1).

There have been a number of ingenious suggestions proposed to lower the central temperature of the Sun with a view to account for the deficit in the solar neutrino flux measured by the chlorine experiment. These have included proposals invoking partial mixing in the solar core which can bring additional fuel of hydrogen to the centre, thus maintaining the nuclear energy production at a slightly lower temperature: the presence of a small admixture of weakly interacting massive particles (WIMPs) in the central regions which would effectively contribute to an increase in the thermal conductivity of

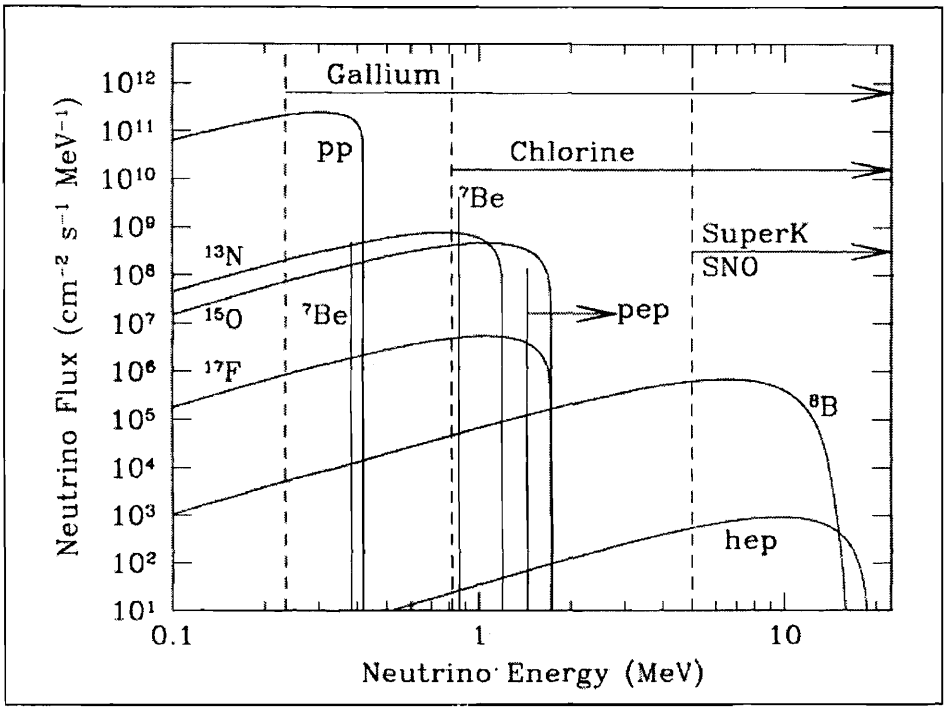

Figure 1. The energy spectrum of neutrinos emitted by each of the 8 nuclear reactions that generate neutrinos in the solar core. For each curve the source of neutrinos is marked in the figure. The dashed vertical lines mark the threshold energy for each of the operating experiment as marked in the figure.

the material in the process diminishing the temperature gradient required to transport the energy flux generated by nuclear reactions; the rapidly rotating solar core; the centrally concentrated magnetic field; lower heavy element abundance at the centre. All such proposals led to a slight reduction in the central temperature causing a lowering of the flux of intermediate and high-energy neutrinos reported by Davis.

Some twenty-five years after the admirable run of the Chlorine experiment, a Japanese set-up consisting of a 680 ton water tank was located about 1 km underground in the Kamioka mine. This experiment was designed to detect charged particles by measuring Cerenkov light through the elastic scattering reaction,

$$\nu_x + e^- \rightarrow \nu_x' + e^- \quad (\text{threshold} = 5.5 \text{ MeV}).$$

The Kamiokande and the upgraded Superkamiokande experiment are sensitive to the capture of only the high-energy ^{8}B neutrinos released by the pp-chain of nuclear reactions. The measured flux from the Superkamiokande experiment is again deficient by a factor of 2 over the total flux predicted by SSM. The Homestake and Superkamiokande experimental measurements are evidently inconsistent with the proposition of resolving the solar neutrino puzzle with a lowering of the central temperature. It turns out such a reduction in the temperature will cause even a larger suppression of the high-energy ^{8}B neutrino flux to which the Superkamiokande experiment is exclusively sensitive because of the extremely high-temperature dependence of the ^{8}B neutrino rate ($\sim T^{25}$). Paradoxically, the Homestake experiment that detects the intermediate as well as high energy neutrinos shows an even larger reduction in the neutrino counting rate. Thus by decreasing the central temperature it is not possible to construct a solar model which simultaneously matches results of both the Homestake and Superkamiokande measurements and we can eliminate a

The solar neutrino puzzle cannot be solved by lowering the central temperature of the Sun.

Different aspects of the solar neutrino puzzle.

cooler solar core as a viable solution of the solar neutrino problem.

Besides these two experiments there are three other radiochemical experiments, GALLEX, SAGE and GNO that use gallium detectors with a relatively low threshold of 0.233 MeV; these are capable of detecting the low-energy pp-neutrinos. The GALLEX, SAGE and GNO experiments report measurements of the solar neutrino counting rate, on an average of 74.7 ± 5.0 SNU. The SSM prediction of the neutrino capture rate for the gallium experiment is 128 ± 8 SNU, again showing a deficit in the measured neutrino counting rate. We are thus led to the conclusion that the experimental efforts and increasingly more refined theoretical models, over the past three and a half decades have only confirmed the discrepancy between the measured and calculated neutrino fluxes.

One of the primary goals of contemporary solar neutrino experiments was to understand the physics of thermonuclear reactions operating in the Sun and more importantly, to constrain the properties of neutrinos. Evidently none of the measurements of neutrino fluxes by the chlorine, water and gallium experiments were consistent with each other, provided we make the assumption that neutrinos have standard physical properties, namely, no mass (and no magnetic moment) and no flavour-mixing during transit from their generation in the solar core to their detection here on Earth, and that the Sun is in thermal equilibrium maintaining a constant luminosity. There are, in fact, considerations based on fairly general arguments independent of any underlying solar models which can be demonstrated to lead to unphysical situations such as a negative flux of ^{7}Be neutrinos coming from the Sun.

A possible resolution of this conundrum is to endow neutrinos with a tiny mass and permit transformation of neutrino flavour during propagation. The electron neutrinos could get transformed into neutrinos of a different flavour along their flight path through the interior of the Sun and of the Earth, or through the interplanetary space between the Sun and the Earth. A fraction of electron neutrinos which are the exclusive by-products of the Sun's nuclear reaction network would then go undetected in some of the solar neutrino experiments. This raises the exciting possibility of non-standard neutrino physics being responsible for the deficit in the measured neutrino fluxes and for the particular need to go beyond the standard model of particle physics. The first compelling evidence for such oscillations of neutrino flavours came a few years ago from the Superkamiokande's analysis of the data on high-energy cosmic ray produced neutrinos in the Earth's atmosphere. The Superkamiokande experiment measured the difference in the up and down fluxes of neutrinos produced by the cosmic ray interaction with the terrestrial atmosphere to demonstrate that neutrino oscillation, indeed, takes place. There was recorded a lower flux of neutrinos coming from underneath than from overhead. Such an asymmetry in the up and down fluxes would arise because of the passage of the upward moving neutrinos through the solid mantle of Earth, while the downward moving neutrinos coming from overhead and generated afresh in the Earth's atmosphere are less likely to undergo any flavour oscillations.

Can neutrinos change their flavour?

The measurements recently reported by the Sudbury Neutrino Observatory (SNO) seem to provide convincing evidence that the solar neutrinos, indeed, change from one flavour to another during their journey from the Sun to Earth. The SNO experiment located at a depth of over 6000 meters of water equivalent in Sudbury uses 1000 tons of heavy water containing the deuterium isotopes of hydrogen for the detection of solar neutrinos, while the Superkamiokande detector contains

Recent results from Sudbury Neutrino Observatory.

ordinary water for measuring the flux of solar neutrinos. In both heavy and ordinary water neutrinos can elastically scatter electrons to produce Cerenkov radiation, but such electron scattering can be caused by any of the three neutrino flavours: electron, muon- and tau -neutrino. The Sudbury Neutrino Observatory is capable of measuring the ^{8}B neutrinos through the following reactions:

$$\nu_e + d \to p + p + e^- \qquad \text{(charged current)}$$

$$\nu_x + e^- \to \nu_x' + e^- \qquad \text{(elastic scattering)}$$

$$\nu_x + d \to \nu_x' + p + n \qquad \text{(neutral current)}$$

Here x stands for electron, muon-, tau-neutrinos.

SNO's heavy water detector is capable of isolating electron neutrinos, because that flavour alone can be absorbed by a deuterium nucleus to produce two protons and an electron. The neutral current (NC) reaction is equally sensitive to all the neutrino flavours, while the elastic scattering (ES) has significantly lower sensitivity to mu and tau-neutrinos compared to electron-neutrinos. SNO has reported the elastic scattering count rate which equals the Superkamiokande event rate to within experimental errors. However, SNO's count of the charged current reaction which is sensitive exclusively to the electron-neutrinos is lower than the SNO/ Superkamiokande event rate recording all the three flavours. This demonstrable difference in the ^{8}B flux deduced from the charged current and elastic scattering rates, at the level of 1.66σ, furnishes reasonably firm evidence that some of the electron neutrinos produced in the Sun's core are transformed into mu- or tau-neutrinos by the time they arrive at the experimental set-ups here on Earth. Recently, the neutral current reaction results have been announced by SNO reporting the flux of mu- or tau-neutrinos at 5.36σ level. Furthermore, the total ^{8}B neutrino flux as measured by the NC reaction is

$(5.09 \pm 0.62) \times 10^6$ cm^{-2} s^{-1}, in agreement with that predicted by the standard solar model. These experimental measurements reassure solar physicists that their simple theoretical models constructed with a minimum of assumptions are essentially correct and that the resolution of the solar neutrino problem should be sought in the realm of particle physics by appealing to the transformation of neutrinos while travelling from the Sun to Earth and/or transiting through the solar/terrestrial matter.

The Mikheyer, Smirnov, Wolfenstein (MSW) effect.

Ever since Raymond Davis announced the first results of his Chlorine experiment at variance with the theoretically predicted neutrino fluxes, the mystery of the missing solar neutrinos has been attracting the attention of scientists. Besides a host of novel astrophysical solutions advanced to alleviate the discordance between theory and observation, there was a bold proposal by Pontecorvo and Gribov, as early as 1969, soon after Davis had announced his results, that the discrepancy between theoretical predictions and the first neutrino experimental measurements could be due to our inadequate understanding of neutrino physics. According to them elusive neutrinos probably suffer from multiple personality disorder and as a result of their split personality, these sub-atomic particles could oscillate among different states during their travel from the Sun to Earth, thus evading detection in their 'easier-to-detect' states in the experimental set-up. The idea was later developed by Mikheyer, Smirnov and Wolfenstein to show that passage of neutrinos through the body of Sun and Earth could further increase their oscillation probability (MSW effect). A comparison of the measured neutrino fluxes with those calculated using the SSM and seismic model provides valuable information about the physical properties of neutrinos by delineating the permissible regions in the neutrino oscillation parameter space.

Is the seemingly tantalising agreement between the theory and observations a mere coincidence, or just another manifestation of the cussedness of Nature! The solar community was therefore, prompted to explore an independent complementary tool to probe the physical and chemical conditions inside the Sun. This was provided by helioseismic studies which have been described in [1]. We should like to conclude by reflecting the feelings expressed by William A Fowler some 30 years ago: "What we are making is mainly a cultural and intellectual contribution – minute though it may be – to the sum total of human knowledge. And that is why we do it and perhaps, this is our apology for what we are doing .... If it should happen to have practical applications, that is all very well – fine and dandy! But we think it is important that the human race understands where the sunlight comes from!"

Suggested Reading

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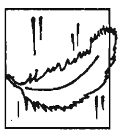

"... conquering matter is to understand it, and understanding matter is necessary to understanding the universe and ourselves: and that therefore Mendeleev's Periodic Table, which just during those weeks we were learning to unravel, was poetry ..." (p.41)

Primo Levi

(Translated by Raymond Rosenthal)
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