BY SMALL STEPS TOWARDS "THE BEGINNING" WHAT HAVE WE LEARNED FROM FIRST RESULTS OF THE PHOBOS DETECTOR AT RHIC?*

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From its start by the Big Bang the history of the Universe can be marked by subsequent phase transitions. In the laboratory it is possible to study some of these phase transitions in the reverse order *i.e.* from low to high temperatures. The subject of this lecture concentrates on the phases which can be studied by collisions of heavy ion nuclei at high energies namely the liquid to gas phase transition for nuclei and the ultimate transitions to quark gluon phase. During the year 2000 the Relativistic Heavy Ion Collider at Brookhaven National Laboratory (RHIC) started its operation. The first experiments concentrated on Au + Au collision at the C.M. energies per nucleon pair $\sqrt{s_{NN}}$ = 56, 130, and 200 GeV. Four detectors: STAR, PHOBOS, BRAHMS, and PHENIX produced first results concerning particle production and properties of hadronic matter at high excitations. The present paper describes in more detail the construction and operation of the PHOBOS detector. The main results obtained by PHOBOS during the first runs of RHIC can be listed as follows:

1. Energy dependence of the charged particle pseudorapidity density near midrapidity for central collisions $(dN_{\rm ch}/d\eta)_{|\eta|<1}$.
2. Centrality dependence of $(dN_{\rm ch}/d\eta)_{|\eta|<1}$.
3. Charged particle density distribution in full the range of η values $|\eta| < 5.4$.
4. Azimuthal anisotropy of events.
5. Ratios of $\overline{p}/p$, K^-/K^+, and π^-/π^+ measured in the midrapidity region within the acceptance of the spectrometer.

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1. Introduction

The main purpose of the PHOBOS detector is to study particles with low transverse momenta P_t emitted in the midrapidity region (rapidity $y \approx 0$) in ultra-relativistic heavy ion collisions. Fast partons with momenta p higher than 1 GeV/c are usually hadronizing at distances of the order of γ fm, where γ is the Lorentz time dilatation factor. Thus it is rather unlikely that fast hadrons will contain information on the state of a blob of matter of the size of 10 fm produced in two heavy nuclei collision. From the Heisenberg relation $\Delta p\,\Delta r \geq 200$ (MeV/c) fm one can easily estimate that a pion with momentum of 20 MeV/c will be produced within the distance of 10 fm thus it is quite interesting to pursue studies of this low energy hadronic spectra in order to get information on the phenomena at large distance scales in ultra-relativistic heavy ion collisions. This was first pointed out by Busza [1]. It should also be mentioned that over 40% of hadrons emitted from the volume of quark–gluon plasma after freeze-out (phase transition to hadronic state) will have the energy lower than $3kT_{\rm c}/2$ where $T_{\rm c}$ is the transition temperature. Numerous lattice simulations as well as calculations based on the so called Hagedorn temperature [2] indicate the value of the phase transition temperature of about 170 MeV. Therefore, studies of particle spectra (mostly pions) well below $p_\pi = 0.5$ GeV/c are highly advisable. PHOBOS detector is designed to precise studies of low energy spectra, multiplicities, angular distributions and angular correlations of particles emitted in heavy ion collisions. The principle of the detector is described in Section 2.

2. The PHOBOS detector

The PHOBOS detector installed at the Relativistic Heavy Ion Collider is presented in Fig. 1. It consists of four subsystems: a 4π multiplicity array, a vertex detector, a two-arm magnetic spectrometer and several detectors which serve to trigger the whole device on the events of collision of two heavy nuclei. The trigger system can also provide informations on the centrality of the collision. All the detectors are silicon surface barrier diodes made of 300 μ wafers with different pad sizes from 0.4 mm to 1 mm in the bend direction. The multiplicity array is a nearly 4π single layer system of detectors which measures the angle and number of particles. It has a shape of an octagon covering the collision region along the beam pipe within the pseudorapidity η range from -3.2 to 3.2 and six silicon ring detectors located on both sides of the vertex which extend the pseudorapity range to $|\eta| \leq 5.4$. The two-arm spectrometer consists of 15 silicon layers located on both sides of the beam axis. The silicon layers are placed between the pole pieces of the double dipole magnet. To minimize the energy losses as well as the background due to scattering of the beam halo the central beam tube of

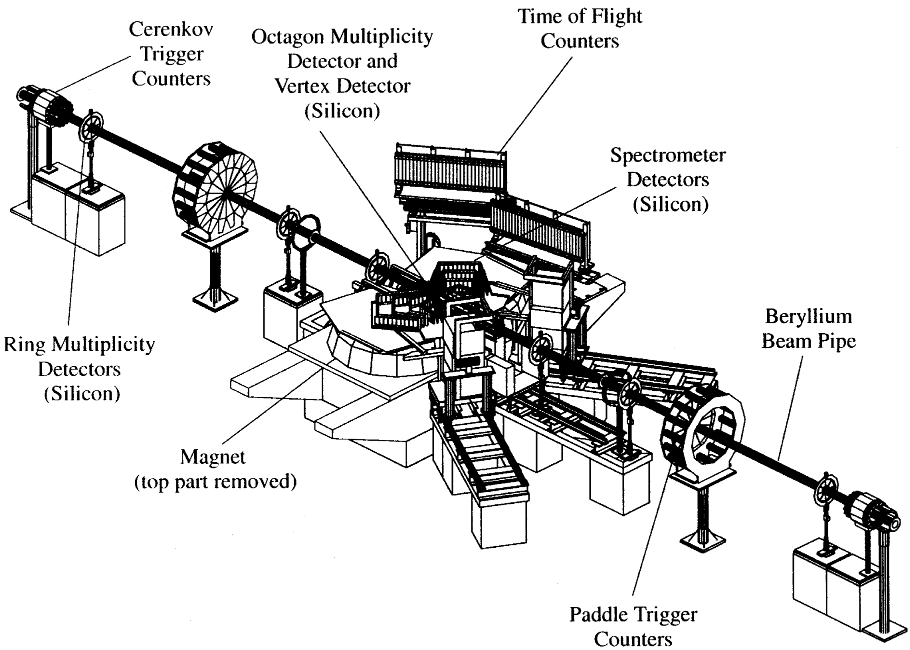

Fig. 1. Schematic layout of the PHOBOS detector from Ref. [3]. The top yoke of the magnet is not shown.

8 cm diameter is made of beryllium of the thickness of 1 mm. The two arm spectrometer cover about 2% of the full solid angle.

Two scintillation paddle detectors (16 paddles each) serve as a trigger which starts the whole read-out system on gold–gold collisions at various centralities. Each paddle gives a signal proportional to the number of charged particles crossing its surfaces. The measured signal may be used to estimate the centrality of the collision, *e.g.*, number of participating nucleons $N_{\rm part}$. In order to avoid secondary particles, which are crossing the paddle at some larger angles and are not coming from the vertex region, readings from the four paddles with largest signal amplitudes are rejected. Two additional pairs of ring detectors *i.e.* the Cerenkov detectors and neutron Zero Degree Counters (ZDC) are used to reduce the beam-gas background. ZDCs are placed at the distance ± 18.5 m from the vertex and are registering beam velocity neutrons not deflected by the dipole magnets of the accelerator. The signals from the ZDCs are showing a nice anti-correlation with the signals from the paddle trigger what serves as an additional proof of the consistency of the whole arrangement. Detailed description of the PHOBOS detector can be found in [3].

3. The multiplicity of charged reaction products

Results of the measurements of the multiplicity of charged particles in the midrapidity region *i.e.* in the interval $|\eta| < 1$ that is in the angular range of $\pm 60°$ around $\Theta = 90°$ against the collision axis are shown in Fig. 2. The

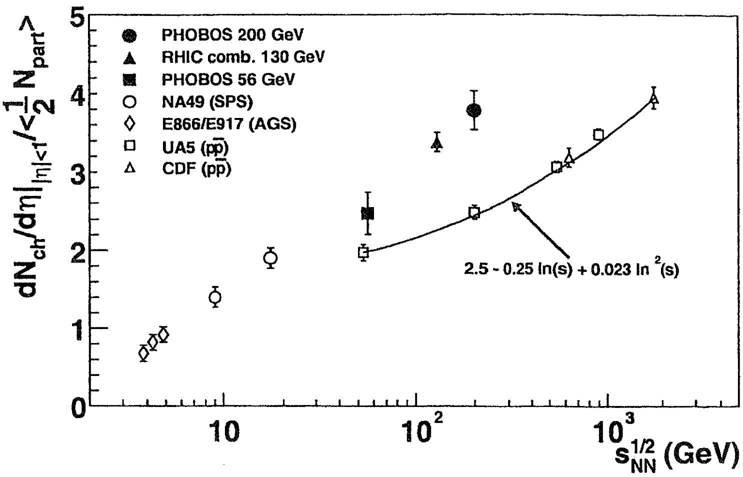

Fig. 2. Energy dependence of the pseudorapidity density normalized per participant pair for central Au + Au collisions. The data are compared with $p - \overline{p}$ data and nucleus–nucleus data from lower energies. From Ref. [30].

multiplicity per unit pseudorapidity measurements $(dN_{\rm ch}/d\eta)_{|\eta|<1} / \langle \frac{1}{2} N_{\rm part} \rangle$ are normalized per participant pair of nucleons for central Au + Au collisions. On the same plot other data at lower energies are plotted from Pb+Pb collisions at SPS (CERN) and Au + Au collisions at AGS (BNL) [3,4]. The data are compared to multiplicities in $\overline{p}$–p interaction from SPS and Tevatron (Fermilab), as well as old data on p–p collision at ISR energies. Within the experimental errors the data on multiplicity in large energy interval 3 GeV $< \sqrt{s_{NN}} \leq$ 200 GeV normalized per participant nucleon pair can be represented by a straight line on the semilogarithmic plot (the solid line in Fig. 3). Thus it can be concluded that in the large energy range the multiplicity is proportional to $\ln \sqrt{s_{NN}}$. Assuming that such proportionality will hold for higher energies we can predict the multiplicity at midrapidity for Pb–Pb collision at $\sqrt{s_{NN}}$ =5.5 TeV *i.e.* for LHC energies as 6.13 per nucleon pair. This has important implications for the mechanism of particle production. For energies lower than 17.2 GeV (the highest SPS energy) the multiplicity of charged particles normalized per nucleon pair is approximately equal to the multiplicity obtained in nucleon–nucleon collisions. This indicates on the validity of the Wounded Nucleon Model [5]. According to this model

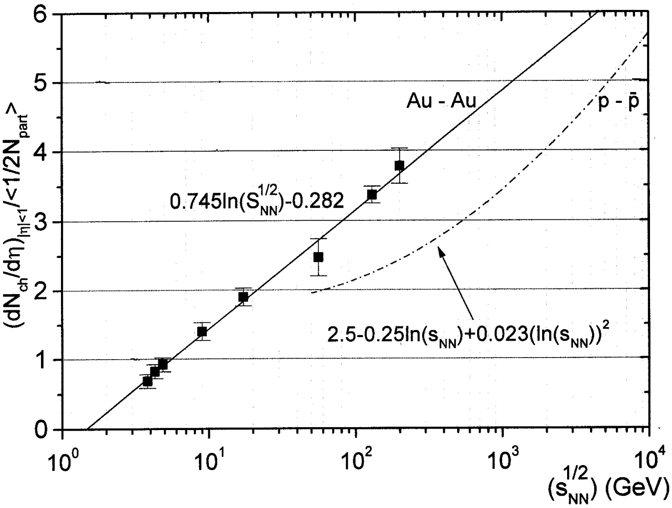

Fig. 3. Experimental data on multiplicity per unit pseudorapidity for Au–Au and Pb–Pb collisions from Ref. [30], fitted by a straight line and extrapolated to higher energies. For comparison the p–$\overline{p}$ data (dash-dotted line) taken from Ref. [31] are shown.

particles are produced as a result of the decay of excited (wounded) nucleons. These nucleons are excited by soft collisions. Each excited nucleon can produce particles only once after it leaves the interaction region so that the multiplicity will be proportional to the number of participants and not to the number of collisions. Multiple soft collisions can only change the excited states of the nucleon but not the fact that it will decay outside of the range of nucleon forces due to the Lorentz time dilatation factor γ. At higher energies when hard collisions between partons become more and more important the contribution from collision with large momentum transfer may reach 37% at 130 GeV, as was shown by Kharzeev and Nardi [6]. So far, theory of the multiplicity of charged particle emission was based on the scaling theory of Koba, Nielsen, Olesen [7] developed by Golokhvastov [8], Wróblewski [9], Szwed *et al.*, [10–12] and Gaździcki *et al.* [13]. The basic assumption that multiparticle production is a scale invariant branching process due to quark–antiquark string breaking leads to the result that the multiplicity distribution is of the lognormal type. In consequence, the calculated average multiplicity in e–e^- and p–p collision scales with energy as $\langle n\rangle = \alpha\exp(\beta\sqrt{s})$, where $\langle n\rangle$ is the average multiplicity and β equals to 0.495. Some authors [13] mention that multiplicity in p–$\overline{p}$ collision at higher energies *i.e.* $\sqrt{s} > 15$ GeV is better fitted with second order polynomial of $\ln(s)$ what can be clearly seen in Fig. 2. Closer examination of experimental data and their extrapolation shown in Fig. 3 leads to the following conclusions:

1. The existing data on multiplicity at midrapidity for Pb–Pb and Au–Au collisions in the energy range from $\sqrt{s_{NN}} = 3$ GeV to $\sqrt{s_{NN}} = 200$ GeV shows a linear scaling with $\ln(\sqrt{s_{NN}})$.

2. Extrapolation of the straight line on the semilog plot allows us to predict the value of $(dN/d\eta)_{|\eta|<1}$ normalized per participant pair as 6.13 for the LHC assuming $\sqrt{s_{NN}} = 5.5$ MeV.

3. Extrapolating the multiplicity curve for p–$\overline{p}$ collisions according to the formula 2.5–0.4 $\ln(s) + 0.02 \ln^2(s)$ we have the value of 5.28 at $\sqrt{s_{NN}} = 5.5$ TeV what leads to the value of 16% for the ratio of the hard to soft collisions, which is smaller than that at $\sqrt{s_{NN}} = 200$ GeV. This may indicate that the number of hard collisions increases also in p–$\overline{p}$ interactions.

4. The values of multiplicity at midrapidity calculated by the Hijing 1.35 model of Wang and Gyulassy [14] for Au + Au collisions above $\sqrt{s_{NN}} = 200$ GeV are strongly exceeding the values extrapolated from the existing experimental data assuming linear $\ln(\sqrt{s})$ dependence.

5. Looking on Fig. 3 it is quite clear that we need urgently more experimental data on the multiplicity at midrapidity for 56 GeV and lower energies down to $\sqrt{s_{NN}} = 20$ GeV. Such data can greatly help to make plausible the extrapolations presented above. The same applies to p–p collisions.

4. Ratios of antiparticles to particles

Using both spectrometer arms and performing subsequent measurements with reversed directions of magnetic fields it was possible to determine the ratios of $\overline{p}/p$, K^-/K^+ and π^-/π^+ [15]. In Table I the obtained values for the above ratios are listed. Assuming a thermal model according to which the hot plasma expands and freeze-out at certain radius R we can infer from the measured ratios of antihadrons to hadrons about the temperature and chemical potential of the system. From the measured ratio of $\langle\overline{p}\rangle/\langle p\rangle$ averaged over various proton energies we can obtain the value of the ratio μ_B/T using the simplified equation:

$$\frac{\langle\overline{p}\rangle}{\langle p\rangle} = \frac{\exp\left(-\frac{\mu_B}{T}\right)}{\exp\left(\frac{\mu_B}{T}\right)} = \exp\left(-2\frac{\mu_B}{T}\right) . \tag{1}$$

Equation (1) is valid under the assumption that the emission occurs from a thermally equilibrated source with equal chemical and thermal freeze-out

TABLE I

The ratios of antiparticle to particle for pions, kaons, and protons from Ref. [15].

$\frac{\langle \pi^- \rangle}{\langle \pi^+ \rangle}$	1.00 ± 0.01(stat) ± 0.02(syst)
$\frac{\langle K^- \rangle}{\langle K^+ \rangle}$	0.91 ± 0.07(stat) ± 0.06(syst)
$\frac{\langle \overline{p} \rangle}{\langle p \rangle}$	0.60 ± 0.04(stat) ± 0.06(syst)

temperatures. At the energy $\sqrt{s_{NN}} = 130$ GeV this may be a plausible assumption [16]. At the SPS experiments at $\sqrt{s_{NN}} = 17.2$ GeV it was shown that these two temperatures may differ *e.g.* $T_{\text{thermal}} < T_{\text{chemical}}$ [17]. Thus from the measured ratio $\langle \overline{p} \rangle / \langle p \rangle = 0.60 \pm 0.04$ we can calculate $\mu_B/T = 0.25 \pm 0.03$ using equation (1). In order to determine the value of the baryochemical potential we need some other constraints either from the measured ratios $\langle K^- \rangle / \langle K^+ \rangle$ or from direct temperature measurements. The baryochemical potential for a realistic range of chemical freeze-out temperatures of 160 to 170 MeV using both values $\langle K^- \rangle / \langle K^+ \rangle$ and $\langle \overline{p} \rangle / \langle p \rangle$ as measured by PHOBOS [15] leads to the value $\mu_B = 45 \pm 5$ MeV using statistical model calculation of Redlich *et al.* [18]. This is much lower than the value of $\mu_{\text{B}} = 240$–270 MeV [18,20] obtained in the statistical model fits to the Pb+Pb data at $\sqrt{s_{NN}} = 17.2$ GeV. This result indicates much closer approach to a baryon free regime at RHIC. The thermal model of particle production was used by Florkowski *et al.* [21] to analyze the particle ratios and P_T spectra measured at RHIC. The fit to the particle ratios yields $T = 165 \pm 7$ MeV and $\mu_{\text{B}} = 41 \pm 5$ MeV. Using these parameters Broniowski and Florkowski calculated the P_T spectra for π, K, and p under the assumption of simultaneous chemical and thermal freeze-out and taking into account contributions from decays of resonances as well as longitudinal and transverse flow-effects. Their calculations are compared to the P_T spectra measured by PHENIX [22] in Fig. 4. One can see that this thermal approach is in a good quantitative agreement with the data. At this point we should mention some analogy between the liquid to gas phase transition for nuclei which occurs around the temperature ~ 10 MeV and transition to QGP which should occur around 170 MeV roughly one and half order of magnitude higher. If we heat-up the nucleus (*e.g.* by passage of fast light particles through heavy nucleus) the nucleus expands until it reaches the freeze-out radius at which the Coulomb repulsion prevails over nuclear attraction. As a consequence the nucleus decay instantaneously into nucleons and fragments

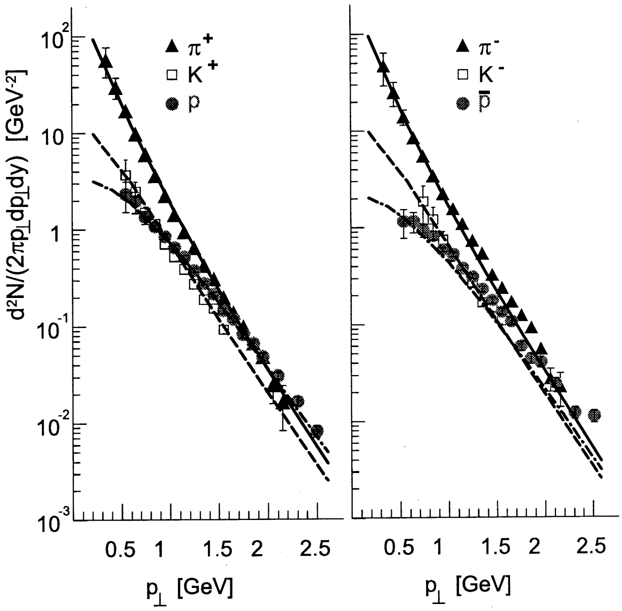

Fig. 4. The $p_\perp$-spectra of pions (solid line), kaons (dashed line), and protons or antiprotons (dashed-dotted line), fitted by the thermal model of Broniowski and Florkowski [21].

according to the available phase space. Some of this fragments are emitted in excited states and will decay further. The spectrum of emitted light fragments, after correction for the decay of excited fragments and collective flow velocity, will reflect the temperature at freeze-out. Quark gluon plasma after its formation will expand thus its temperature lowers and reaches the freeze-out configuration. At this moment hadrons are formed and some of them are simply hadronic resonances. Hadrons are emitted reflecting the temperature at freeze-out but their spectrum as measured by external observer is slightly modified by decaying resonances and hydrodynamic flow velocities. This was first taken into account by Broniowski and Florkowski [21].

Finally some comments can be made for the Au + Au collision at $\sqrt{s_{NN}} = 130$ GeV. From the Bjorken formula [23]:

$$\varepsilon = \frac{dN}{dy} \frac{\langle M_{\mathrm{T}} \rangle}{\pi R^2 \tau}\,, \tag{2}$$

where ε is the energy density, dN/dy is the multiplicity per unit of rapidity, M_{T} is the transverse mass of the emitted particles, τ is the proper formation time of the order of 10^{-23} s and R is the radius of colliding nuclei. We see that the energy density is proportional to the specific multiplicity. That means that if the multiplicity in central Au + Au collision at 130 GeV is 70% higher than at SPS experiment [24] for Pb + Pb collision at 17.2 GeV the energy density at RHIC should be 1.7 times higher than at SPS. The experimental results after proper analysis show that the temperature is nearly constant and the baryo-chemical potentials is five times smaller at RHIC experiments than at SPS. Let us now recall the old idea which can be traced back to suggestion made by Van Hove in 1982 [25]. This can be illustrated by a simple graph shown in Fig. 5, where the temperature T is plotted against the energy density ε.

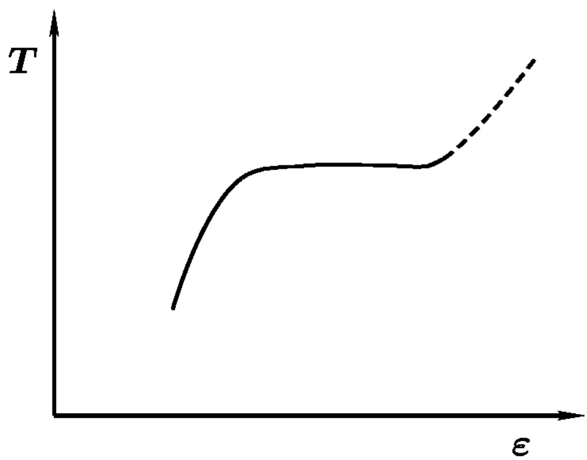

Fig. 5. Temperature T as a function of energy density ε.

The plateau in this figure indicates that we have reached the “melting” point of nucleon gas into QGP. Originally it was expected that the end of the plateau in Fig. 5 the rise of temperature with increasing energy density will be seen. However, this may not be the case. We are not registering partons but hadrons. QGP after expansion hadronizes at freeze-out temperature *i.e.* at the transition temperature. This will be reflected by the spectrum of emitted hadrons which will have kinetic energy distributions corresponding to transition temperature $T_{\rm c}$ around 160–180 MeV. Thus we can conclude that the value of the temperature determined from kinetic energy spectra at SPS energies and RHIC energies may indicate that at $\sqrt{s_{NN}} = 130$ GeV we are deep in the region of QGP. The value of baryonic chemical potential can be a good indicator how far away we are from full conversion of hadrons to QGP.

5. Other information on the mechanism of two heavy ion collision

The data on centrality dependence of the normalized charged particles multiplicity $(dN_{\rm ch}/d\eta)/(0.5\,N_p)$ at $\sqrt{s_{NN}} = 130$ GeV [30] are in good agreement with the Pirner and Yuan model of enhanced mini jet production in Au + Au collisions from gluons with large transverse momenta [26]. This indicates on the important influence of the transverse momenta of gluons on the observed multiplicity at midrapidity. Measurements of the charge particle density distribution in the range of η values $|\eta| < 5.4$ as well as azimuthal anisotropy of events provides further constraints on the different models of reaction including the Hijing model [27], Kharzeev and Levin model [28] and many others. The maximal value v_2 of the second Fourier-expansion coefficient of the azimuthal distribution relative to the reaction plane measured for peripheral collisions increases with energy what can exclude several models of reaction mechanism as shown by Teaney [29]. The elliptic flow v_2 result implies the presence of the pressure gradient in the initial stage of reaction. Ratio of multiplicities at midrapidity as measured at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 130$ GeV can also serve to exclude several models *e.g.* Hijing with jet quenching [4]. Further discussion of the validity of various models will require more experimental data and obviously exceeds the scope of this lecture.

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