Sensitivity of YAC to Measure the Light-Component Spectrum of Primary Cosmic Rays at the ‘Knee’ Energies (Postprint)

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Abstract

一种新型大气簇射芯探测器阵列（YAC：羊八井大气簇射芯探测器阵列）已在中国西藏研制，用于测量膝区能区的初级宇宙线成分，主要关注轻成分。由 16 个探测器组成的原型实验（YAC-I）已于 2009 年 5 月在西藏羊八井（海拔 4300 米）建成并投入运行。YAC-I 安装在 Tibet-III AS 阵列中并协同工作。本文通过蒙特卡罗模拟检验了 YAC-I+Tibet-III 阵列对膝区能区宇宙线轻成分的灵敏度，考虑了实际 YAC-I+Tibet-III 阵列的观测条件。轻成分与其他成分的甄别采用人工神经网络（ANN）方法。模拟结果表明，我们的方法估计的轻成分能谱能够在 10% 误差范围内很好地重现输入谱，并将存在约 30% 的系统误差，主要由所使用的初级粒子与相互作用模型引起。研究发现，全规模 YAC 与 Tibet-III 阵列相结合是研究宇宙线成分的有力工具，特别是可用于获取膝区能区质子和氦核的能谱。

Full Text

Sensitivity of YAC to Measure the Light-Component Spectrum of Primary Cosmic Rays at the “Knee” Energies

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Abstract. A new air-shower core-detector array (YAC: Yangbajing Air-shower Core-detector array) has been developed to measure the primary cosmic-ray composition at the “knee” energies in Tibet, China, focusing mainly on the light components. The prototype experiment (YAC-I) consisting of 16 detectors has been constructed and operated at Yangbajing (4300 m a.s.l.) in Tibet since May 2009. YAC-I is installed in the Tibet-III AS array and operates together.

In this paper, we performed a Monte Carlo simulation to check the sensitivity of YAC-I+Tibet-III array to the cosmic-ray light component of cosmic rays around the knee energies, taking account of the observation conditions of actual YAC-I+Tibet-III array. The selection of light component from others was made by use of an artificial neural network (ANN). The simulation shows that the light-component spectrum estimated by our methods can well reproduce the input ones within 10% error, and there will be about 30% systematic errors mostly induced by the primary and interaction models used. It is found that the full-scale YAC and the Tibet-III array is powerful to study the cosmic-ray composition, in particular, to obtain the energy spectra of protons and helium nuclei around the knee energies.

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1. Introduction

It is well known that the all-particle spectrum of primary cosmic rays follows a power law of $dJ/dE \propto E^{-\gamma}$, but steepens at energies around 4×10^{15} eV where the power index γ changes sharply from ~ 2.7 to ~ 3.1 [1, 2]. Such structure of the all-particle energy spectrum is called the "knee", which is considered to be closely related to the origin, acceleration and propagation mechanism of cosmic rays. In order to explain the existence of the knee, many hypotheses and mechanisms [3, 4] have been proposed. Although all these approaches can well describe the knee structure, there are much discrepancies in the prediction of the individual components at the knee region. Thus, it is critical to measure the primary chemical composition or mass group at energies 50-10,000 TeV, especially to measure the primary energy spectra of individual component and determine a break energy of the spectral index for individual component.

Direct cosmic-ray measurements on board balloons or satellites are the best way to study the chemical composition, while the maximum energy they can cover is up to 10^{14} eV/nucleon at most due to limited detection area or exposure time. We may have no choice but to rely on ground-based air-shower (AS) measurements to study the primary chemical composition around the knee.

The study of cosmic-ray composition around the knee was done by a hybrid experiment of the emulsion chambers (ECs), the burst detectors (BDs) and the AS array (Tibet-II), where ECs and BDs of total area 80 m² were set up near the center of the AS array and operated for three years [5, 6, 7]. The threshold energy of ECs capable of analyzing the fine structure of AS cores is about 1 TeV, so that it is not difficult to separate the AS events induced by light-component of protons and helium nuclei, while the energy range of primary particles is limited to be above ∼ 200 TeV for protons and ∼ 400 TeV for helium nuclei [6]. This experiment suggests that the flux of light component is less than ∼ 30% of the total, resulting in that the knee is dominated by nuclei heavier than helium [7]. A demerit of this experiment is that there are few statistics of the high-energy core events due to the high detection threshold energy of the experiment as mentioned above. To improve this problem, a new air-shower core detector named YAC (Yangbajing Air shower Core detector) has been developed and improved so as to meet our requirements.

One important improvement is to lower the detection threshold energy of primary particles to several times 10 TeV, about one order of magnitude smaller than the previous experiment. With this improvement, the energy spectra of individual components measured by YAC will overlap with those of direct measurements, which may help us to examine the knee of light component, such as "proton knee" or "helium knee" . Another important improvement of YAC is its ability to count the number of shower particles passing through each detector in a wide dynamic ranging from 1 to 10^6 particles, making it possible to observe the primary cosmic rays in the energy range from ∼ 10 TeV to ∼ 10 PeV.

Until now, we have constructed and operated YAC-I as a prototype of full-scale YAC comprising 400 core detectors. YAC-I is a small array consisting of 16 core detectors which were placed near the center of the Tibet-III AS array as shown in Fig. 1 [Figure 1: see original paper], while being able to observe a lot of AS-core events in the energy around 10^{14} eV by the operation of a few months. As the primary composition around this energy region is fairly well known by the direct observations [8, 9, 10], the data from YAC-I may be used to test the interaction models such as SIBYLL2.1, QGSJETII-04 and EPOS-LHC being currently used in the Monte Carlo (MC) simulations. In this paper, we discuss the performance and sensitivity of YAC for observing light-component spectrum of primary particles through MC simulations based on the YAC-I experiment.

2. YAC-I Experiment

[Figure 1: see original paper] shows a schematic view of YAC-I and the Tibet-III AS array. Open squares represent scintillation detectors of the Tibet-III array (for details of the Tibet-III, see the paper [1]), while filled red squares represent core detectors of the YAC-I array. YAC-I consists of 16 detector units of 0.2 m^2 each, which cover an area of about 10 m^2. Each detector of YAC-I consists of a lead plate with a thickness of 3.5 cm (6.3 radiation lengths), a supporting iron plate with a thickness of 0.9 cm (0.5 radiation lengths), and a plastic scintillator with a thickness of 1 cm.

Each core detector of YAC-I comprises a plastic scintillator with dimensions of 40 cm × 50 cm and a lead plate with a thickness of 3.5 cm (6.3 radiation lengths) placed on top of the scintillator. The lead plate is used to select AS particles and cores capable of having sufficient energy to create cascade showers in the lead plate and pass through the scintillator. The plastic scintillator in the core detector is divided into 10 pieces of 4 cm width, and the scintillation lights are collected through wavelength shifting (WLS) fibers as shown in Fig. 2 [Figure 2: see original paper]. Such design ensures the geometrical uniformity of detector response within 5%. The details about the hardware of the YAC detector are described in [11, 12].

Two photomultiplier tubes (PMTs) of high-gain (HAMAMATSU: R4125) and low-gain (HAMAMATSU: R5325) are equipped to cover a wide dynamic range from 1 MIP (Minimum Ionization Particle) to 10^6 MIPs as seen in Fig. 2. The corresponding linearity and saturation effect of PMT and scintillator were examined using cosmic-ray muons and electron beams provided by the beam facility of BEPCII (Beijing Electron Positron Collider, IHEP, China) [13]. The stability of the PMT gain was checked and corrected using cosmic-ray muons.

In this experiment, the YAC-I array works to observe air-shower cores, and their accompanying ASs are observed simultaneously with the Tibet-III AS array. The Tibet-III provides information on the arrival time and direction of each air shower and its AS size corresponding to the energy of the primary particle [1]. When a YAC-I event is triggered, its accompanying AS is simultaneously recorded by the Tibet-III array, and the matching between YAC-I and Tibet-III events is made by their arrival time stamps recorded by a GPS clock.

3. Monte Carlo Simulation

We have carried out a full Monte Carlo (MC) simulation on the development of air showers in the atmosphere using the simulation code Corsika [14] (version 7.3500). Three hadronic interaction models, including SIBYLL2.1 [15], EPOS-LHC (v3400) [16], and QGSJETII-04 [17], are used to generate the air-shower events in the atmosphere.

For the primary cosmic rays, we examined three composition models, namely, “He-poor”, “He-rich”, and “Gaisser-fit”models, in order to evaluate the systematic errors attributable to primary composition models. The “He-poor” model is based on the HD (Heavy Dominant) model mentioned in the paper [1], and it is slightly revised to match with the new all-particle energy spectrum [1], to become the new “He-poor” model. The “He-rich” model is the “Model B (a slightly harder spectrum than the previous one by taking account of the nonlinear effects)” mentioned in the paper [4]. The “Gaisser-fit” model is the “three-population” model mentioned in the paper [18]. The proton spectra of the former two models are fitted to the direct measurements at low energy and are consistent with the spectrum obtained from the Tibet-EC experiment at high energy. The He spectrum of the He-poor model coincides with the results from RUNJOB, but the He spectrum of the He-rich model coincides with the results from JACEE, ATIC2, and CREAM. The Gaisser-fit model fits to a higher He model (almost the same as our He-rich model) at the low energy range and to the KASCADE-QGSJET data at the high energy range in which light components

(P and He) dominate in the chemical composition.

In all models mentioned above, each component is summed up so as to match the all-particle spectrum with a sharp knee, which was obtained with the Tibet-III AS array [1]. Table 1 summarizes the fractions of the components (P, He, Medium, and Fe) of the three composition models in given energy regions. The energy spectra of individual components (or mass groups) for the three primary models are shown in Fig. 3 [Figure 3: see original paper]. It is seen that all the individual components of the three models in the low energy range (less than 100 TeV) are in good agreement with direct measurements while differing significantly at higher energy. The all-particle spectra of the three models, however, coincide with each other and reproduce the sharp knee structure as well.

In this simulation, primary cosmic rays at the top of the atmosphere within zenith angles smaller than 60 degrees are thrown into the atmosphere isotropically, and the minimum energy of primary cosmic rays is set to 40 TeV. All shower particles in the atmosphere are traced down to a minimum energy of 1 MeV. The AS events generated are randomly dropped onto an area of 32.84 m × 32.14 m, which is 15 m wider on each side of the YAC-I array. This dropping area is large enough to collect the AS events with more than 99.5% efficiency under our core-event selection conditions (see below in the text). Observation of the MC events is made with the same method as that of the experiment.

The detector responses to shower particles falling on the detectors of the (YAC-I+Tibet-III) array are calculated using Geant4 [21] (version 9.5), where the detector performance, trigger efficiency, and effective area are adequately taken into account based on the experimental conditions. The number of charged particles passing through the scintillator is defined as the PMT output (charge) divided by that of the single-particle peak. The single-particle peak is determined by a probe calibration [1, 11] using cosmic rays, typically muons. The value of the single-particle peak is measured as 1.98 MeV for YAC-I detectors and 6.28 MeV for the Tibet-III detectors. These values are used in this MC simulation.

The main purpose of this work is to check the sensitivity of YAC to observe the light component of primary cosmic rays as well as to evaluate the systematic errors by adopting different primary composition models and interaction models mentioned above. For this, we selected five combinations of interaction models and primary composition models. Four combinations–SIBYLL2.1+He-rich, SIBYLL2.1+He-poor, EPOS-LHC+He-poor, and EPOS-LHC+Gaisser-fit–are used to check the sensitivity of YAC to the light component and uncertainties due to the adoption of different composition models. The other three combinations–SIBYLL2.1+He-poor, QGSJETII-04+He-poor, and EPOS-LHC+He-poor–are used to check the interaction models and also uncertainties under the same primary composition model. It is worth pointing out here that there is no serious difference among the current interaction models on particle production in the forward region and proton-air inelastic cross sections in our concerned energy region from 10 TeV to 10^4 TeV, since all the models are well tuned using recent accelerator data including LHC, while there are big differences among primary composition models because of a lack of direct observation data at energies above ~ 200 TeV.

The number of air-shower events generated for each model is 7.40×10^7, 6.57×10^7, 4.67×10^7, 6.25×10^7, and 5.18×10^7, respectively, as shown in Table 2 . The analysis of these MC events was made by the same method used in the experiment.

4. Analysis

Information on the size N_e and arrival direction of each air shower event hitting both YAC-I and Tibet-III arrays can be easily obtained from the MC events observed with the Tibet-III AS array simultaneously. Details of its analysis are found in the paper [1].

From the YAC-I array, we can obtain the following five quantities reflecting the characteristics of AS cores: (1) N_{hit}, the number of "fired" detectors with $N_b \geq 200$, where N_b is the number of particles (burst size) observed by each core-detector; (2) N_{top}, the maximum N_b among the fired detectors; (3) $\sum N_b$, the total sum of N_b of fired detectors; (4) $\langle R_i \rangle$, the mean lateral spread defined as $\langle R_i \rangle = \sum (N_b \times r_i)/\sum N_b$, where N_b denotes the number of particles observed in the i-th fired detector and r_i represents the lateral distance from the burst center (X_c, Y_c), where $(X_c, Y_c) = (\sum N_b \times x_i/\sum N_b, \sum N_b \times y_i/\sum N_b)$; (5) $\langle N_b R_i \rangle$, the mean energy-flow spread defined as $\langle N_b R_i \rangle = \sum (N_b \times r_i)/N_{\mathrm{hit}}$. It is confirmed that the five quantities mentioned above are basic and sufficient to separate the light component (P+He) from others. Use of an ANN method [22] may further improve the quality of separation.

Table 2 shows the statistics of the data sets selected in MC simulation. In order to obtain the light-component spectrum using data from both YAC-I and Tibet-III arrays, we select high-energy core events by imposing the conditions $N_{\mathrm{top}} \geq 1500$ and $N_e \geq 80,000$. The mode energy of primary particles producing such high-energy core events is then estimated to be about 200 TeV. The statistics of the data sets selected based on the five models are listed in Table 2. Shown in Fig. 4 [Figure 4: see original paper] is the effective $S\Omega$ of the YAC-I array to observe AS-core events satisfying the event selection conditions, where S denotes the detection area and Ω the solid angle. The effective $S\Omega$ depends weakly on the model used, but its difference is found to be smaller than 25% in our concerned energy range.

5. Results and Discussion

We check the sensitivity of the YAC array to the interaction models and primary cosmic-ray models using the high-energy core events selected under the conditions discussed in the previous section.

5.1 Total Burst-Size Spectrum and Mean Lateral Spread of AS-Cores

It is well known that the absolute intensity of the total burst sizes depends sensitively on the increase of cross sections and inelasticity, and also on the primary cosmic-ray composition. Shown in Fig. 5 [Figure 5: see original paper]-(a) are the integral total burst-size spectra ($\sum N_b$ spectra) obtained by the respective MC model for comparison. The spectra obtained by the five MC models are compared with each other by taking the flux ratio to that from the SIBYLL2.1+He-rich model in Fig. 5-(b). It is seen that the EPOS-LHC+Gaisser-fit model gives the highest flux in all N_b region. According to our MC simulation, the observed AS cores in the size region of $N_b = 2 \times 10^3 - 4 \times 10^5$ are produced mostly by the light component (P+He) with primary energies of several times $10^{14} - 10^{15}$ eV. The fraction of light component in the primary flux of this energy region is about 66% for the Gaisser-fit model, while about 55% for the He-rich model and 42% for the He-poor model, as seen in Table 1. It should be noted, however, that about 70% of the observed high-energy core events are originated by the light component; that is, the contribution from other nuclei is fairly small.

Here, we discuss the uncertainties due to different interaction models in reference to the spectrum of high-energy core events. Before entering the discussion, we should first remind that the production rate of high-energy core events is most sensitive to the energy per nucleon of primary particles. Thus, the mean energy per nucleon of helium nuclei is 1/4 that of protons when compared at the same primary energy, and also the interaction mean free path of helium nuclei in air is about half that of protons.

For the He-poor model, it is seen that the flux of protons is slightly higher than that of helium nuclei or almost the same in the energy region above about 300 TeV, and also their power indices are almost the same, as learned from Fig. 3 and Table 1. If we combine this with the above discussion, it may be allowed to ignore the contribution from helium nuclei to the core events observed in this primary model; that is, they can be regarded as those produced by protons. Under this assumption, it may be noticed from Fig. 5-(b) that the flux values from SIBYLL2.1, QGSJETII-04, and EPOS-LHC using the same primary He-poor model match well within an error smaller than 10%, which may be attributed to uncertainties due to the interaction models used. A deviation of QGSJETII-04 in the core-size region above about 2×10^5 may be due to low statistics of the events, that is, within statistical fluctuation (at most 2 level).

On the other hand, when we arrange the light component flux of protons and helium nuclei in descending order in the $10^2 - 10^4$ TeV region, it becomes Gaisser-fit > He-rich > He-poor. It is then confirmed that the flux of core events is in the same order as the primary light-component flux, and also the shape of each primary spectrum is well reflected in the corresponding core-event spectrum, as seen in Fig. 5-(b). A typical example is seen in the case of the Gaisser-fit primary model. This means that high-energy core-event observation with YAC is very sensitive to the primary light-component spectrum.

A correlation between $\langle N_b R_i \rangle$ and N_b is shown in Fig. 5-(c). This figure tells us that the Gaisser-fit primary model gives smaller lateral spread than others, while the QGSJETII-04+He-poor model gives larger spread than others. As protons with long interaction mean free path can penetrate deep into the atmosphere and produce AS cores near the observation level, they result in smaller lateral spread. The Gaisser-fit primary is light-component dominant, as seen in Fig. 3, so the core spread from this model should be smaller than others. When the primary model is fixed as He-poor, the mean spread of QGSJETII-04 is slightly larger than that of SIBYLL2.1. This may depend slightly on the interaction model since the energy spectrum of secondary particles in the very forward region (Feynman $x \sim 0.1 - 0.3$) produced at collision in the SIBYLL2.1 model is harder than that of QGSJETII-04; that is, the former contains slightly more very high-energy secondaries than the latter. The difference in intensity and lateral spread between both models could be attributed to the number of very high-energy particles that penetrate deep into the atmosphere.

It should be noted that the lateral spread of AS-cores is mostly caused by Coulomb scattering of shower electrons and positrons in the atmosphere, not by transverse momentum of secondaries produced at collisions except within the depth of 1-2 radiation lengths from the interaction point in the atmosphere. In connection with this, the energy loss of AS cores generated by QGSJETII-04 may be faster than those by SIBYLL2.1, resulting in lower AS-core intensity. Hence, a precise AS experiment like the (YAC + Tibet-III AS) array will be able to examine the interaction models to some extent.

5.2 Sensitivity of YAC-I to Observe the Light-Component Spectrum Around the Knee

In this analysis, we use the ANN technique to separate the light component from others. This method is shown to be quite effective for such purpose, as confirmed by our previous works [6, 7]. In this ANN analysis, we use the following seven quantities: (1) N_{hit}, (2) $\sum N_b$, (3) N_{top}, (4) $\langle R_i \rangle$, (5) $\langle N_b R_i \rangle$, (6) N_e, and (7) θ (zenith angle). These are input to the ANN with 35 hidden nodes and 1 output unit. To train the ANN in separating light-component (P+He) from other nuclei, the input patterns for light-component and others are set to 0 and 1, respectively. We then define a critical value of T_c to calculate the corresponding purity and selection efficiency of the selected (P+He)-like events.

Figure 6 [Figure 6: see original paper] shows the ANN output pattern value (T) distribution trained using the EPOS-LHC+He-poor model. As seen in this figure, events with $T \leq T_c = 0.4$ could be regarded as (P+He)-like events, and the average selection purity and efficiency over the whole energy range of (P+He)-like events are 95% and 76%, respectively.

Table 3 summarizes the ratios of (P+He)/All at three phases of analysis, before and after ANN training based on the MC models. In this table, the second column represents the ratio of primary (P+He) flux to the all-particle flux in the energy region above 40 TeV. The third column represents the ratio of true (P+He) events contained in the observed high-energy core events selected by the condition mentioned in the text. The fourth column represents the ratio of true (P+He) events contained in the ANN-trained core events with $T \leq T_c = 0.4$. The fifth column represents the ratio of the number of ANN-trained core events with output $T \leq 0.4$ to that of all ANN-trained core events ($0 \leq T \leq 1$).

Thanks to the performance of the YAC-I array, the ratio of (P+He)/All before ANN training (core events) has already reached $\sim 70\%$ by the core-event selection conditions ($\sim 87\%$ for the Gaisser-fit model, as seen in Table 3). With ANN training, the purity of selected (P+He)-like events is further increased up to $\sim 95\%$, as learned from Table 3. This high-quality data set is used for reconstructing the light-component primary spectrum. Table 3 teaches us that after ANN training, the difference in selection purity and efficiency is within $\sim 6\%$ among the three hadronic interaction models and $\sim 8\%$ among the three primary composition models. Overall uncertainties due to ANN training for the MC models are then estimated to be about 10%.

5.3 Expected Light-Component Spectrum

Using the ANN trained by the EPOS-LHC+He-poor events, we select the (P+He)-like events from all observed events and also obtain the selection purity and efficiency. The primary energy E_0 of each selected event is then estimated using the AS size N_e obtained by the Tibet-III. The relation between air shower size N_e and primary energy E_0 is expressed as

$$E_0 = \alpha \times N_e^{\beta},$$

where the parameters α and β are estimated from AS events generated by the MC for the Tibet-III AS array, while α and β depend on the zenith angle of air showers. Details of this procedure are described in the paper [1]. Shown in Fig. 7 [Figure 7: see original paper] is the correlation between E_0 and N_e of the (P+He)-like events selected by the ANN method. The solid line denotes the best-fit curve for this correlation, and parameter values of $\alpha = 0.794$ and $\beta = 1.005$ are obtained for air showers with $\sec\theta \leq 1.1$. The energy resolution is also estimated as about 25% at energies around 200 TeV.

We also checked the dependence of the correlation between N_e and E_0 on the interaction and primary composition model and obtained similar relationships in the other models. We then found that there is less than 10% difference in the determination of primary energy using different interaction and primary composition models.

Figure 8 [Figure 8: see original paper] shows the estimated primary energy spectrum of the light component (P+He) in comparison with the assumed primary spectrum. It is seen that the estimated energy spectrum well reproduces the assumed one within about 10% errors. Almost the same results are obtained for other MC models.

In this work, we discuss the systematic errors coming from the models used in the MC simulation for deriving the primary (P+He) spectrum using the (YAC-I+Tibet-III) array. The systematic errors caused by each step of the analysis procedures are investigated, including the dependence of the MC data on the interaction models, the primary composition models, and the algorithms for primary mass identification. We summarize these systematic errors as follows: (1) errors due to the observation efficiency ($S\Omega$ of (P+He)) depending on the interaction and primary composition models are found to be smaller than 25%; (2) errors due to the selection of (P+He)-like events with ANN training are about 10%, in which the model dependence on purity and efficiency is totally included; (3) errors due to the estimation of primary energy using the conversion from N_e to E_0 are 10%, in which the dependence on both interaction and primary composition models is taken into account; (4) errors due to the reconstruction procedures of the primary light-component spectrum from the observed core events are estimated to be smaller than 10%. The total systematic errors are then estimated to be about 30% as the square root of the quadratic sum of those four systematic errors, which may be somewhat overestimated because of a little correlation among the four error estimation parts.

6. Summary

In this paper, we have carried out a full MC simulation to examine the capability of measuring the energy spectrum of the primary light component (P+He) of cosmic rays at the knee energies using the (YAC-I+Tibet-III) array. The models used in this MC simulation are SIBYLL2.1, EPOS-LHC (v3400), and QGSJETII-04 for the interaction, and He-poor, He-rich, and Gaisser-fit for the primary cosmic-ray composition. The Corsika code was used to generate AS events in the atmosphere, and the Geant4 code was used to treat the shower particles entering the detectors. The air-shower core events observed with the YAC-I array were analyzed to select those induced by the light component using the ANN technique. In this paper, we focused on the sensitivity of the YAC-I array to observe the light component of cosmic rays around the knee and discussed the systematic errors coming from the models used in the MC, which are indispensable for obtaining results that should be as independent of the model as possible. It is shown that the YAC+Tibet AS array is powerful for studying the primary cosmic-ray chemical composition, in particular, for obtaining the energy spectrum of the light component (P+He) of cosmic rays at the knee energies. A full-scale YAC consisting of 400 core detectors covering more than 5000 m^2 could be operated together with the Tibet-III array in the very near future.

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Note: Figure translations are in progress. See original paper for figures.