Toward UrQMD Model Description of \textit{pp} and \textit{pC} Interactions at High Energies

V. Uzhinsky

Laboratory of Information Technologies, JINR, Dubna, Russia

It is found that UrQMD model version 3.3 does not describe NA61/SHINE Collaboration data on \(\pi^-\)-meson production in \(pp\) interactions at energies 20 – 80 GeV. At the same time, it describes quite well the NA49 Collaboration data on the meson production in \(pp\) and \(pC\) interactions at 158 GeV. The Collaborations do not consider feedback of \(\eta\)-meson decays. All versions of the UrQMD model assume that \(\eta\)-mesons are “stable”. An inclusion of the decays into calculations leads to 2–3 % increase of the meson production which is not enough for description of the data. Possible ways of the model improvements are considered.

Conclusions of the paper are: accounting of \(\eta\)-meson decays is not essential for a description of experimental data; a new tuning of the UrQMD model parameters is needed for a successful description of \(pp\) and \(pC\) interactions at high energies; inclusion of the low mass diffraction dissociation in the UrQMD model would be desirable.

1 \textit{pp} interactions

The NA61/SHINE Collaboration is going to obtain a high precision data on \(\pi^-\)-meson inclusive cross sections in \(pp\) interactions at \(P_{\text{lab}} = 20, 31, 40, 80\) and 158 GeV/c. Some preliminary results are published in the paper [1]. The NA49 Collaboration has published the high precision data on \(\pi^\pm, K^\pm\), proton and antiproton spectra in \(pp\) [2, 3, 4] and \(pC\) [5] interactions at 158 GeV/c. The NA61/SHINE Collaboration has the analogous data for \(pC\) interactions at 31 GeV/c [6]. There were some attempts to describe the last data in the modern Monte Carlo models – FLUKA, VENUS, FTF and UrQMD [6, 7, 8]. As it was shown in the paper [7] the \(pC\) data at 31 GeV/c can be described in the UrQMD model after a small improvement of the model code. An analysis of the above mentioned data can point on other improvements of the model.

The UrQMD model [9] is a tool for analysis of nucleus-nucleus interactions at high energies. It is implemented as a Monte Carlo code [10] which is widely used at design of future experiments at FAIR [11] and NICA [12] facilities. Its validation for hadron-nucleon interactions presented at HEPWEB server [13] is not complete, and can be improved now.

![Figure 1](image_url)

Figure 1: Rapidity distributions of \(\pi^-\)-mesons in \(pp\) interactions. Closed points are preliminary NA61/SHINE data [1], the open points are the data reflected at mid-rapidity. Magenta squares are the NA49 data at 158 GeV/c [2]. Lines are the UrQMD 3.3 model calculations: a) calculations with default values of the model parameters; b) calculations with \(\eta\)-meson decays.

As it is shown in Fig. 1a the model version 3.3 with default values of the parameters cannot describe the NA61/SHINE Collaboration data on \(pp\) interactions. Only at \(P_{\text{lab}} = 158\) GeV/c there is an agreement between the model calculations and the NA49 data.
At the calculations, $\eta$-mesons were considered as "stable" ones. At the same time the Collaborations did not take into account feedbacks of the $\eta$-meson decays. An inclusion of the decays in the calculations leads to few percent increase of the spectra in central regions (see Fig. 1b) which is not sufficient for a good description of the data.

The same conclusion about the role of the $\eta$-meson decays can be done at an application of the model to the NA49 data [2, 4] (see Fig. 2).

Figure 2: Rapidity distributions of mesons in $pp$ interactions at $P_{lab} = 158$ GeV/c. Points are experimental data [2, 4]. Lines are UrQMD 3.3 model calculations: solid lines are the calculations with default values of the parameters, dashed lines are the calculations with accounting of $\eta$-meson decays.

The following changes were introduced in the UrQMD model code (file urqmd.f) for a consideration of the decays:

```fortran
  c  
  c Main program 
  c
  lbm(8,102)=1 ! Setting decays of eta-meson ! Uzhi
  branmes(0,102)=0.39d0 ! Setting decay to gg 39% ! Uzhi
  branmes(8,102)=0.61d0 ! Setting decay to 3 Pi 61% ! Uzhi
  mc0
  mp0
  noc0
  c
  c loop over all events
  c

  The following lines were added and closed below in the file:
  c is particle unstable
  * if(dectime(i).lt.1.d30) then ! Uzhi
    if((dectime(i).lt.1.d30).or.(ityp(i).eq.102)) then !Forcing eta-meson decay
```
As known, the UrQMD model uses the Fritiof model [14] for simulations of hadronic interactions at high energies. It also simulates various binary reactions like that $NN \rightarrow N\Delta, NN \rightarrow NN^*, NN \rightarrow N\Delta^*$, $NN \rightarrow \Delta\Delta, NN \rightarrow \Delta N^*$ and $NN \rightarrow \Delta\Delta^*, \Delta N^*$. They are very important at low energies. At the considered energies the Fritiof processes are mainly responsible for particle production in the central region, at $y_{\text{cms}} \sim 0$. The above mentioned binary processes give contributions in the projectile and target fragmentation regions. Thus, a simple way to improve the situation is a decreasing of the binary reaction cross sections. The decreasing in 3 times gives results presented in Fig. 3.

Figure 3: Energy dependence of meson inclusive cross sections in $pp$ interactions in the central region. Points are experimental data [12]. Lines are the UrQMD 3.3 model calculations: solid line is a calculation with default parameters; dashed line is a calculation with accounting of the $\eta$-meson decays; dotted line is a calculation with decreased binary reaction cross sections; dot-dashed line is a calculation with 50% probability of the single diffraction dissociation.
As seen, the decreasing allows to describe meson production at 20, 31, 40 and 80 GeV/c. At larger energies it leads to an overestimation of the inclusive cross sections. Because the cross sections of the binary reactions are small at high energies, the main contribution to the spectra is connected with the Fritiof processes. The processes are single diffraction dissociation and "non-diffractive" interaction (more exactly, two-vertex diffraction dissociation).

A probability of the single diffraction is a decreasing function of an energy in the Fritiof model which contradicts with known experimental data. Thus, the spectra at mid-rapidity are growing faster than it is needed. This can be erased fixing the probability at 50 %, for example. As seen in Fig. 3 the assumption allows to describe the data at 158 GeV/c. The calculations underestimate the data at 80 GeV/c. Summing up, one can conclude that accurate parameterizations of the binary reaction cross sections and the single diffraction cross sections are needed for a correct description of experimental data on pp interactions.

The following changes were introduced in the file scatter.f to implement the decreasing of the binary reaction cross sections:

```fortran
    call crossx(line, sqrts, ityp1, iso31, fmass(ind1),
    & ityp2, iso32, fmass(ind2), sigma(ii-2))
    if((ityp1.le.100).and.(ityp2.le.100).and.(ii gt.4).and.(ii.le.10) ! Uzhi
    & .and.(sqrts.ge.3.5d0)) sigma(ii-2)=sigma(ii-2)/3. ! Uzhi
    else ! detailed balance:
```

The implementation of the increased probability of the single diffraction in the file make22.f is more complicated:

```fortran
    if((sqrts.ge.3.5d0)) then ! Uzhi
81 continue
   c 100 tries for excitation, otherwise elastic scattering
   ntry=ntry+1
    if(ntry.gt.1000)then
        write(*,*)'make22: too many tries for string exc. ->elastic/
        & deexcitation'
        write(*,*)' i1, i2, m1, m2, e: ',i1,i2,m1,m2,e
        i1=i1old
        i2=i2old
        goto 13
    endif
   c string-excitation:
   c get string masses ms1,ms2 and the leading quarks
    call STREXCT(IFdiq1,IFqrk1,i1,M1m,
    & IFdiq2,IFqrk2,i2,M2m,E,
    & iexopt,
    & ba1,ms1,ba2,ms2,
    & ifdiq3,ifqrk3,ifdiq4,ifqrk4)
    c the boost parameters are now fixed for the masses ms1, ms2. If the
    c masses will be changed, set the parameter fboost to "false":
    fboost=.true.
    if((ms1.le.msmin1).or.(ms2.le.msmin2)) goto 81 ! Uzhi
    c accept deexcitation of one of the hadrons:
    * if(ms1.le.msmin1.and.ms2.ge.msmin2)then
    * ms1=massit(i1)
    * fboost=.false.
    * else if(ms2.le.msmin2.and.ms1.ge.msmin1)then
    * ms2=massit(i2)
    * fboost=.false.
    c don't accept elastic-like (both masses too low):
    * else if(ms1.lt.msmin1.and.ms2.lt.msmin2)then
    c
```
c in case of deexcitation new masses are necessary

* if(ms1.le.msmin1)then
  ms2=fmsr(msmin2,e-ms1)
  fboost=.false.
* elseif(ms2.le.msmin2)then
  ms1=fmsr(msmin1,e-ms2)
  fboost=.false.
* endif

else !----------------------------------------- Uzhi

  c single diffractive, mass excitation according 1/m
  * goto 81
  * endif

  call STREXCT(IFdiq1,IFqrk1,ib1,M1m,
  & ifdiq2,ifqrk2,ib2,M2m,E,
  & iexopt,
  & ba1,ms1,ba2,ms2,
  & ifdiq3,ifqrk3,ifdiq4,ifqrk4)

  if(ranf(0).ge.0.5d0) then !-------- Targ. diffr. ! Uzhi
    ms1=massit(i1) ! ! Uzhi
    ms2=fmsr(msmin2,e-ms1) ! ! Uzhi
    fboost=.false. ! ! Uzhi
  else !-------- Proj. diffr. ! Uzhi
    ms2=massit(i2) ! ! Uzhi
    ms1=fmsr(msmin1,e-ms2) ! ! Uzhi
    fboost=.false. ! ! Uzhi
  endif !----------------------------------------- ! Uzhi

endif !----------------------------------------- ! Uzhi

Figure 4: Rapidity distributions of protons and antiprotons in pp interactions at 158 GeV/c. Points are experimental data [3]. Lines are the UrQMD 3.3 model calculations: solid lines are the calculations with default parameters; dashed lines are obtained at the 50% probability of the single diffraction; dotted lines are the calculations at the assumption that the leading particle effect is valid for all baryons.

Very complicated situation takes place with baryon spectra in pp interactions. It is presented in Fig. 4. As seen, the UrQMD model predicts a dip in the proton rapidity spectrum at $y_{cms}$ $\sim$ 2.5 and a maximum at $y_{cms}$ $\sim$ 1.75. A peak at $y_{cms}$ $\sim$ 2.8 reflects the single diffraction dissociation. The experimental spectrum has more simple structure. The main difference between the experimental data
and the model calculation is connected with proton multiplicity in the inelastic \( pp \) collisions. As seen, the model overestimate the multiplicity.

The increasing of the probability of the single diffraction leads to an abnormal increase of the forward peak and a small decreasing of the proton yield in the central region (see dashed curves in Fig. 4). The difference between the experimental data and the calculations in the central region cannot be explained by newly produced protons because the corresponding multiplicity of newly produced antiprotons is small.

Leading protons and neutrons originated from primary protons are treated in the model differently from other baryons - \( \Delta, \Delta^*, N^* \) and so on. A special fragmentation function is used for a production of the leading nucleons. Assuming that all baryons obey the leading particle effect\(^1\), we obtain dotted curves in Fig. 4. As seen, the assumption does not allow to improve the situation.

In order to find a process what can be responsible for a filling of the dip presented in the proton spectrum at \( y_{c.m.s.} \sim 2.5 \), let us look at proton spectra in various processes considered by the UrQMD model. The spectra are shown in Fig. 5.

![Proton and neutron spectra in various processes of the UrQMD model](image)

**Figure 5:** Proton and neutron spectra in various processes of the UrQMD model. Solid and dashed lines, correspondingly.

As seen, the \( NN \rightarrow N\Delta \) process can give an yield in the dip region, but according to the reggeon phenomenology its cross section must decrease as \( 1/s \) where \( s \) is CMS energy squared. It is also true for the \( NN \rightarrow \Delta\Delta \) process. The processes \( NN \rightarrow \Delta N^* \) and \( NN \rightarrow \Delta\Delta^*, \Delta N^* \) can give the needed contributions. It is expected that their cross sections decrease as \( 1/\sqrt{s} \). In the processes, systems with small masses (\( M_X < 3–5 \) GeV) are created in an association with \( \Delta \)-resonance. In the reggeon phenomenology a low mass diffraction dissociation is considered – \( NN \rightarrow N + X \). A mass distribution of system \( X \) looks like \( 1/M_X^2 \). Its cross section is proportional to the elastic cross section, \( \sigma_{LMD} \approx 0.55 \sigma_{el} \).

Thus, the cross section does not decrease with energy growth. The diffraction can fill the dip of the proton spectrum. The above selected processes - \( NN \rightarrow \Delta N^* \) and \( NN \rightarrow \Delta\Delta^*, \Delta N^* \), can imitate the diffraction in the UrQMD model. In order to include the diffraction, cross section of the process \( NN \rightarrow \Delta N^* \) was increased in the `scatter.f` file:

```fortran
call crossx(iline,sqrts,ityp1,iso31,fmass(ind1),
```

\(^1\)It was implemented in the file `string.f` opening the commented line "c & (abs(IDENT(I)).eq.1110))then" and closing the previous line " & (abs(IDENT(I)).eq.1120 .or.abs(IDENT(I)).eq.1220 )then".
This improves the proton spectrum in the dip region and π-meson rapidity spectra (see Fig. 6).

![Rapidity spectra of particles in pp interactions at 158 GeV/c. Points are the experimental data \cite{3}. Lines are the UrQMD model calculations with imitation of the low mass diffraction.](image1)

Figure 6: Rapidity spectra of particles in pp interactions at 158 GeV/c. Points are the experimental data \cite{3}. Lines are the UrQMD model calculations with imitation of the low mass diffraction.

Now the main problem is a large protons multiplicity in the final states. The excess of protons in the model can be explained by a damped multiplicity of strange baryons. To check the hypothesis we need an exact data on hyperon production in pp interactions. To a good luck, the NA49 Collaboration in the paper \cite{2} presented in Fig. 22 $p_T$ integrated density distributions, $d\sigma/dx_F$, of $\Lambda$, $\Sigma^+$ and $\Sigma^-$ hyperons ($x_F = 2 p_z/\sqrt{s}$). The data are shown in Fig. 7 below in a comparison with model calculations.

![dn/dx_F distributions of $\Lambda$, $\Sigma^+$ and $\Sigma^-$ hyperons in pp interactions at 158 GeV/c. Points are experimental data \cite{2}. Lines are the UrQMD 3.3 model calculations with default parameter values.](image2)

Figure 7: $dn/dx_F$ distributions of $\Lambda$, $\Sigma^+$ and $\Sigma^-$ hyperons in pp interactions at 158 GeV/c. Points are experimental data \cite{2}. Lines are the UrQMD 3.3 model calculations with default parameter values.

As seen, the model really underestimates the hyperon production in the most interesting region $x_F > 0.3$, and overestimates the yield at $x_F \sim 0$. All attempts to improve the description were not successful. Maybe, the deficit of $\Lambda$ hyperons at $x_F > 0.3$ is caused by the fact that many $\Lambda$ hyperons are produced in the model – $\Lambda(1116)$, $\Lambda(1405)$, $\Lambda(1520)$ and so on. It seems that due to a dominance of
heavy Λ hyperons and decays of heavy Λ hyperons, Λ(1116) has a soft spectrum. Because the simulation algorithm has a complicated structure it is too difficult to improve the situation.

2 \( p\bar{C} \) interactions

The UrQMD model with default parameters values and with the accounting of the \( \eta \)-meson decays describes rather well the NA49 data on \( \pi \)-meson production in \( p\bar{C} \) interactions at 158 GeV/c (see solid curves in Fig. 8). At the same time, the model overestimates the proton yield in the central and target fragmentation regions. The increase of the probability of the single diffraction to 50 \% for the improvement of the proton spectrum at large rapidities in \( pp \) interactions does not help (see dotted curves in Fig. 8). The peak at \( y_{CMS} \sim 2.7 \) is saved, but the proton production in the target fragmentation region is underestimated. The \( \pi \)-meson data are underestimated also. The form of the proton spectrum is not reproduced.

The imitation of the low mass diffraction gives nearly the same results (see dashed lines in Fig. 8). For implementation of the imitation, the other changes were done in scatter.f in order to introduce an energy dependence of the process:

```fortran
    call crossx(iline,sqrts,ityp1,iso31,fmass(ind1),
        ityp2,iso32,fmass(ind2),sigma(ii-2))
    if((ityp1.le.100).and.(ityp2.le.100).and.(ii.ne.3).and. ! Uzhi
        (ii.le.10).and.(sqrts.ge.3.5d0)) sigma(ii-2)=0. ! Uzhi
    if((ityp1.le.100).and.(ityp2.le.100).and. ! Uzhi
        (ii.eq.8).and.(sqrts.ge.3.5d0)) sigma(ii-2)=0.55*sigma(3) ! Uzhi
else ! detailed balance:
```

Figure 8: Rapidity distributions of \( \pi^\pm \)-mesons and protons in \( p\bar{C} \) interactions at 158 GeV/c. Points are experimental data [5]. Lines are the UrQMD 3.3 model calculations: solid lines are the calculations with the accounting of the \( \eta \)-meson decays; dashed lines are the calculations with the imitation of the low mass diffraction; dotted lines are results obtained at the 50 \% probability of the single diffraction.
Results of simulations of pC interactions at 31 GeV are presented in Figs. 9, 10 in a comparison with the NA61/SHINE data [1,6] by the solid lines. Thin lines are the calculations with default parameter values and the η-meson decays. Thick ones are the calculations with the imitation of the low mass diffraction. As seen, the results are rather close to each other. The calculation results reasonably agree with the π^+ data at all angles. The model overestimates the π^- data at all angles, and reproduces qualitative the proton data [1].

**Figure 9:** Momentum spectra of π± and protons in pC interactions at 31 GeV/c. Points are experimental data [1,6]. Lines are the UrQMD 3.3 model calculations with the η-meson decays: thick solid lines (green) are the calculations with the imitation of the low mass diffraction; thin solid lines (black) are the calculations with default parameter values; dashed lines are the calculations for pp interactions with default values of the model parameters; dotted lines are the calculations for pp interactions with the imitation of the low mass diffraction.

In order to understand the behaviour of the calculations, let us look at results of simulations of pp interactions re-normalized on an inelastic pC cross section (252 mb). The matter is, an average multiplicity of intra-nuclear collisions in pC interaction is close to one according to the Glauber approximation. Thus, we can expect that properties of pC interactions will not be very different from properties of pp interactions. In Figs. 9, 10 dashed lines are the calculations for pp interactions performed with default values of the model parameters and with accounting of the η-meson decays. As seen, the calculation underestimates the π^+- and π^- -meson data. Let us remind, that this variant of the calculations gave the
Collaboration has all opportunities to measure proton spectra in 
\( p p \) imitation of the low mass diffraction.

similar results for \( p \) data (see dotted curves in Figs. 9, 10). It is very strange, that the two variants of the calculations give similar results for \( p p \) interactions. The imitation of the low mass diffraction dissociation gives results close to the default values of the model parameters; dotted lines are the calculations for Figure 10: Momentum spectra of \( \pi \) proton-neutron (\( pn \)) to the model calculations. It is explained by the fact, that there is no peak in the proton spectrum of \( \theta < 1.2 \text{ GeV/c} \). It would be very useful to study the region more carefully. I think, the NA61/SHINE \( p \) not resolved quite well in old bubble chamber experiments (typically, proton identification was done at \( p < 1.2 \text{ GeV/c} \)). It is directly connected with the binary reactions with the low mass diffraction. It is located in the target fragmentation region which was not resolved quite well in old bubble chamber experiments (typically, proton identification was done at \( p < 1.2 \text{ GeV/c} \)). It would be very useful to study the region more carefully. I think, the NA61/SHINE Collaboration has all opportunities to measure proton spectra in \( pp \) interactions in the region.

Proton spectra in \( pp \) interactions are very interesting. As seen, there is a broad peak in the calculated proton spectrum at \( \theta < 20 \text{ mrad} \) and \( p \sim 2 \text{ GeV/c} \). It is directly connected with the binary reactions with the low mass diffraction dissociation. It is located in the target fragmentation region which was not resolved quite well in old bubble chamber experiments (typically, proton identification was done at \( p < 1.2 \text{ GeV/c} \)). It would be very useful to study the region more carefully. I think, the NA61/SHINE Collaboration has all opportunities to measure proton spectra in \( pp \) interactions in the region.

As seen also in Fig. 9, the peak is practically disappeared in \( pC \) interactions at \( \theta < 20 \text{ mrad} \) according to the model calculations. It is explained by the fact, that there is no peak in the proton spectrum of proton-neutron (\( pn \)) interactions. \( pp \) and \( pn \) collisions are presented in equal amount.

Figure 10: Momentum spectra of \( \pi^\pm \) and protons in \( pC \) interactions at 31 GeV/c. Points are experimental data [1, 6]. Lines are the UrQMD 3.3 model calculations with the \( \eta \)-meson decays: thick solid lines (green) are the calculations with the imitation of the low mass diffraction; thin solid lines (black) are the calculations with default parameter values; dashed lines are the calculations for \( pp \) interactions with default values of the model parameters; dotted lines are the calculations for \( pp \) interactions with the imitation of the low mass diffraction.
The peak is presented in the model proton spectra of \( pp \) interactions at all angles, and is not seen in the \( pn \) calculations. The experimental data on \( pC \) interactions show a plateau at \( p \approx 2-5 \text{ GeV/c} \) and \( 20 < \theta < 140 \text{ mrad} \). The VENUS model calculations have the plateau very close to the experimental one \[1\]. The FLUKA model gives the peak at small momenta and \( 20 < \theta < 100 \text{ mrad} \). So, there is a problem in other models with accurate simulations of the binary reactions or the low mass diffraction dissociation in hadron-nucleus interactions. A correct implementation of the low mass diffraction dissociation at a simulation of hadron-nucleus interactions requires a lot of efforts, but the theoretical framework (see for example \[15, 16\] and references there) exists which simplifies the task.

For further analysis it is useful to re-plot the NA61/SHINE data in other form shown in Fig. 11. There a particle rapidity is used instead of momentum.

Now it is clear, that the \( \pi^- \)-meson data at \( \theta < 60 \text{ mrad} \) belong to particles produced in the projectile fragmentation region. The data at larger angles show the particle production in the central region.

The proton data at \( 20 < \theta < 60 \text{ mrad} \) are relating to the most interesting region where many proton production mechanisms are mixing in the projectile fragmentation region. The data at low momenta (less than 5 GeV/c) are connected with proton production in the target fragmentation region.

The projectile and target fragmentation regions are not determined quite well. In the reggeon phenomenology, their size is about 1 – 1.5 in rapidity. At projectile momentum 31 GeV/c, the target fragmentation region in \( y_{\text{lab}} \) extends from 0 to 1.5, the projectile fragmentation region is from 2.5 to 4. This definition was used above in the paper.

**Conclusion**

- Accounting of \( \eta \)-meson decays is not essential for a description of experimental data.
- A new tuning of the UrQMD model parameters is needed for a successful description of \( pp \) and \( pC \) interactions at high energies.
- Inclusion of the low mass diffraction dissociation in the UrQMD model would be desirable.
- The experimental data by NA49 and NA61/SHINE Collaborations are very useful for improvement of the UrQMD model.

The author is thankful to A. Galoyan for interest to the work, and to B. Popov for very useful remarks.

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