Parameterized Spectral Distributions for Meson Production in Proton-Proton Collisions

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Abstract

Accurate semiempirical parameterizations of the energy-differential cross sections for charged pion and kaon production from proton-proton collisions are presented at energies relevant to cosmic rays. The parameterizations, which depend on both the outgoing meson parallel momentum and the incident proton kinetic energy, are able to be reduced to very simple analytical formulas suitable for cosmic-ray transport through spacecraft walls, interstellar space, the atmosphere, and meteorites.

Introduction

In order to solve cosmic-ray transport problems, a detailed understanding of the proton-proton interaction is needed. Galactic cosmic rays consist of approximately 85-percent protons (ref. 1) and solar cosmic rays consist almost entirely of protons and \( \alpha \)-particles, whereas geomagnetically trapped particles in the Van Allen belts consist of protons and electrons (ref. 2). The interstellar medium itself consists primarily of hydrogen (protons) and helium (ref. 3). Hence, the proton-proton collision is the most common and most numerous interaction between cosmic rays and the interstellar medium, as well as within the solar system and the Earth’s atmosphere.

Proton transport can be adequately modeled by using the Boltzmann equation in the straight-ahead approximation (ref. 2), which is given as

\[
\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S(E) + \sigma \phi(x,E) = \int_E f(E',E') \phi(x,E') dE'
\]

where \( S(E) \) is the proton stopping power, \( \sigma \) is the media macroscopic cross section, \( \phi(x,E) \) is the particle flux density, \( f(E,E') \) is the secondary-particle differential cross section in terms of secondary-particle energy \( E \) and proton energy \( E' \), and \( x \) is a scaling variable. This straight-ahead approach is used in current transport codes for particle propagation through various media (refs. 4–7).

One major shortcoming of the work done to date is that although the secondary-particle-production cross section \( f(E,E') \) in equation (1) is taken to include all possible secondary particles, codes have not yet been run using meson cross sections (ref. 2). In this paper, parameterizations of cross sections for charged pions and kaons suitable for use in equation (1) will be provided.

The numerical approach currently used in solving equation (1) implements the cumulative energy spectrum, which is related to \( f(E,E') \) above as follows (ref. 2):

\[
F(r,r') = \int_0^{r'} f(E,E') dE
\]

where the residual range \( (r) \) is given by \( r = \int dE'/S(E') \).

For a very thorough analysis of proton transport and a detailed explanation of the numerical procedure for solving equation (1), the reader is referred to Wilson et al. (ref. 2). Such an approach requires that the spectral distribution \( f(E,E') \) be calculated a large number of times, thus making it impractical to utilize complicated analytical formulas for \( f(E,E') \). Hence, the parameterizations derived herein will be presented in the simplest possible terms (without losing accuracy, of course).

An interaction cross section can be written in various forms, and high-energy physicists are interested in the Lorentz-invariant form \( E d^3\sigma d^3p \) (where \( \sigma \) is the total cross section and \( p \) is an energy momentum), which can be calculated from first principles using quantum field theory and is thus a convenient way to check theory with experiment. In this light, all early theoretical and experimental work done with mesons is presented in Lorentz-invariant form (refs. 8–11).

However, \( f(E,E') \) from equation (1) is the energy-differential cross section \( d\sigma/dE \) (or spectral distribution). The Lorentz-invariant cross section can still be used as it contains all the information one might need (including angular and spectral distributions as well as the total cross section). It now becomes a matter of retrieving this information.

In one of the early papers (ref. 11), all then-available accelerator data were gathered, and a very accurate parameterization of the Lorentz-invariant cross section was fit to the data. The aim of the current work is to utilize this representation of the Lorentz-invariant cross section in order to generate a representation of the spectral distribution that will then be parameterized as a simple function of incident proton energy and secondary meson momentum. The final result will provide the proper differential cross section for equation (1).

Symbols

\[ A_1 \quad \text{parameter from table 1, } \text{mb/(GeV}^2/c^3) \]
\[ A_2, C, C_2 \quad \text{parameters from table 1, } (\text{GeV}/c)^{-1} \]
\[ C_1, \gamma \quad \text{parameters from table 1, dimensionless} \]
parameters from table 1, \((\text{GeV}/c)^{-2}\)

speed of light

c.m. center-of-mass frame

differential cross-section element, mb

differential momentum element, \(\text{GeV}/c\)

energy, \(\text{GeV}\)

continuous spectrum \(f(E, E')\) from equation (2)

kaon

mass, \(\text{GeV}/c^2\)

energy-momentum four vector

momentum vector, \(\text{GeV}/c\)

parameter from equation (5)

residual range from equation (2)

proton stopping power from equation (1)

Mandelstam energy variable

scaling variable used in representation of Lorentz-invariant cross section

ratio of c.m. momentum to maximum transferable momentum

parameters in equation (14)

scattering angle

cross section, mb

particle flux density from equation (1)

Subscripts:

max maximum

p proton

s secondary particle

\(\pi\) pion

\(\perp\) perpendicular

\(/\!/\) parallel

Invariant Cross Section

The Lorentz-invariant cross section is given in terms of the following scaling variable (refs. 11 and 12):

\[
\bar{x} = \left[ \frac{1}{s} \left( p_{\perp}^2 + m_s^2 \right) \right]^{1/2}
\]  

\(x_{\perp}\) is the ratio of the parallel component of the center-of-mass (c.m.) momentum to the maximum transferable momentum, \(p_{\perp}\) and \(p_{\parallel}\) are the perpendicular and parallel components of the c.m. momentum, respectively, \(s\) is the Mandelstam energy of the system, and \(m_s\) is the secondary-particle rest mass.

In terms of this variable, the following parameterizations are then given (ref. 11) for pions:

\[
E \frac{d^3\sigma}{d^3p} = \frac{A_1}{1 + (4m_{\pi}^2/s)^2} \exp \left[ \frac{-A_2p_\perp}{1 + (4m_{\pi}^2/s)} \right]
\]  

where

\[
q = \frac{C_1 + C_2p_\perp + C_3p_{\parallel}^2}{1 + (4m_{\pi}^2/s)}
\]  

and for kaons:

\[
E \frac{d^3\sigma}{d^3p} = A_1 (1 - \bar{x})^C \exp(-A_2p_\perp)
\]  

where the parameters \(A_1, A_2, C, C_1, C_2, C_3, \) and \(\gamma\) are given in table 1, and \(m_p\) is the proton rest mass.

Now, if the spectral distribution is to be written in simple terms (i.e., constants, mass, momenta, and energies of the interacting particles), then it will be desirable to first express the Lorentz-invariant cross section in such terms. Specifically, the Mandelstam energy variable \(s\) and the fractional momentum \(x_{\perp}\) must be simply represented.

The Mandelstam representation of the energy for any system \(A + B \rightarrow C + D\) is defined as

\[
s = \frac{(p_A + p_B)^2}{c^2}
\]  

where \(p_A\) and \(p_B\) are energy-momentum four vectors, given by \(p_N = EN/cp_N\), where the bold-faced \(p_N\) represents the usual three-dimensional momentum vector. This can then be rewritten as (see appendix A)

\[
s = m_A^2 + m_B^2 + (2E_Am_p/c^2)
\]  

For the current problem, \(A\) and \(B\) are protons and \(E_A\) is the total incident proton energy (given by the sum of the proton kinetic energy \((T_{\text{lab}})\) and the rest mass \((m_p)\). Thus, the following representation is given:

\[
s = 4m_p^2 + 2m_pT_{\text{lab}}
\]  

The fractional momentum \(x_{\perp}\) is given by \(p_{\parallel}/p_{\text{c.m. max}}\) (ref. 11), where \(p_{\text{c.m. max}}\) is the maximum transferable momentum allowed by the kinematics in the center-of-mass frame. For the arbitrary system
Table 1. Parameters From Equations (4), (5), and (6) Used in Representation of Invariant Cross Section

<table>
<thead>
<tr>
<th>Particle</th>
<th>$A_1$, mb/(GeV$^2$cm$^3$)</th>
<th>$A_2$, (GeV/c)$^{-1}$</th>
<th>$\gamma$</th>
<th>$C_1$, (GeV/c)$^{-1}$</th>
<th>$C_2$, (GeV/c)$^{-1}$</th>
<th>$C_3$, (GeV/c)$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>153</td>
<td>5.55</td>
<td>1</td>
<td>5.3667</td>
<td>-3.5</td>
<td>0.8334</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>127</td>
<td>5.3</td>
<td>3</td>
<td>7.0334</td>
<td>-4.5</td>
<td>1.667</td>
</tr>
<tr>
<td>$K^+$</td>
<td>8.85</td>
<td>4.05</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^-$</td>
<td>9.3</td>
<td>3.8</td>
<td>8.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$A + B \rightarrow C + D$, $P_{c.m.,max}$ is given by (ref. 13 and appendix A)

$$P_{c.m.,max} = \left[ \frac{(s - m_c^2 c^4 - M^2 c^4)^2 - 4 m_c^2 M^2 c^8}{4 s} \right]^{1/2}$$  \hspace{1cm} (10)

where

$$M^2 = (m_A + m_B)^2$$  \hspace{1cm} (11)

Once again, for the current problem, this simplifies to

$$P_{c.m.,max} = \left[ \frac{(s - m^2 c^4 - 4 m_p^2 c^4)^2 - 16 m^2 m_p^2 c^8}{4 s} \right]^{1/2}$$  \hspace{1cm} (12)

Hence, this allows the Lorentz-invariant cross sections from equations (4) and (6) to be expressed solely in terms of the masses, momenta, and energies of the particles (and the parameters given in table 1).

**Spectral Distribution**

The spectral distribution $d\sigma/dE$ is expressed in terms of the invariant cross section via (ref. 11 and appendix A)

$$\frac{d\sigma}{dE} = \frac{\pi}{p_{\parallel}} \int \frac{E}{d^3 p} d(p_{\parallel}^2)$$  \hspace{1cm} (13)

By inserting the invariant cross sections from equations (4) and (6) into equation (13) and integrating, a representation of $d\sigma/dE$ will be produced in terms of proton kinetic energy ($T_{lab}$) and meson parallel momentum ($p_{\parallel}$). Because of the nonlinear exponential form of equations (4) and (6) and the nonlinear integration in equation (13), the integrals cannot be performed analytically. A numerical procedure utilizing adaptive Gaussian 32-point quadrature was implemented (see the computer program in appendix B); this procedure produced the data points seen in figure 1, which shows the spectral distribution for both positively and negatively charged pions and kaons at a variety of proton energies.

By fitting a function of $p_{\parallel}$ and $T_{lab}$ to the data in figure 1, the parameterization will be solved. Clearly, the data are well represented by decreasing the exponentials, and the solid-line curves in the figures represent the best fits obtained by utilizing the following exponential function to represent $d\sigma/dE$:

$$\frac{d\sigma}{dE} = \pi \frac{\alpha}{p_{\parallel}} \exp (-\beta p_{\parallel}^2)$$  \hspace{1cm} (14)

where $\alpha$, $\beta$, and $\chi$ vary with respect to the incident proton kinetic energy ($T_{lab}$) and must be parameterized as such. This procedure is accomplished by determining which values of $\alpha$, $\beta$, and $\chi$ best match the various proton energies from equation (14) with the output from equation (13), and then by finding functions that accurately provide the same values if given simply the proton kinetic energy ($T_{lab}$). The following functions were found to be extremely accurate:

For $\alpha$,

$$\alpha = \alpha_1 \ln (\alpha_2 + T_{lab}) + \alpha_3 \ln (\alpha_4 + T_{lab})^2 + \alpha_5$$  \hspace{1cm} (15)

for $\beta$,

$$\beta = \beta_1 T_{lab}^{\beta_2} \ln (\beta_3 + T_{lab})^{-\beta_4} - \beta_5 T_{lab}^{-\beta_6}$$  \hspace{1cm} (16)

and for $\chi$,

$$\chi = \chi_1 T_{lab}^{\chi_2} + \chi_3 T_{lab}^{\chi_4} + \chi_5$$  \hspace{1cm} (17)

where the subscripted parameters of equations (15), (16), and (17) are given in table 2. The accuracy of
Table 2. Parameters for Representations of $\alpha$, $\beta$, and $\chi$ Used in Equations (15), (16), and (17)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\pi^+$</th>
<th>$\pi^-$</th>
<th>$K^+$</th>
<th>$K^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1$</td>
<td>1.6209</td>
<td>2.0555</td>
<td>0.513</td>
<td>1.0023</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>-0.992</td>
<td>2.5949</td>
<td>3.1993</td>
<td>15.612</td>
</tr>
<tr>
<td>$\alpha_3$</td>
<td>-0.958</td>
<td>-0.546</td>
<td>-0.0421</td>
<td>-0.0711</td>
</tr>
<tr>
<td>$\alpha_4$</td>
<td>-0.0217</td>
<td>689.37</td>
<td>-0.582</td>
<td>2.1746</td>
</tr>
<tr>
<td>$\alpha_5$</td>
<td>2.5884</td>
<td>21.24</td>
<td>-0.6736</td>
<td>-2.7214</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>57.4728</td>
<td>72.1723</td>
<td>25.4335</td>
<td>66.5962</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>-0.6054</td>
<td>-0.6595</td>
<td>-0.5313</td>
<td>-0.5619</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>0.7049</td>
<td>0.7049</td>
<td>-0.1231</td>
<td>-0.122</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>-0.534</td>
<td>-0.5335</td>
<td>-0.9639</td>
<td>-0.9198</td>
</tr>
<tr>
<td>$\beta_5$</td>
<td>42.169</td>
<td>51.658</td>
<td>12.887</td>
<td>28.343</td>
</tr>
<tr>
<td>$\beta_6$</td>
<td>-0.7979</td>
<td>-0.8771</td>
<td>-0.8233</td>
<td>-0.8742</td>
</tr>
<tr>
<td>$\chi_1$</td>
<td>1.9096</td>
<td>1.8773</td>
<td>2.3452</td>
<td>33.621</td>
</tr>
<tr>
<td>$\chi_2$</td>
<td>1.6939</td>
<td>1.4223</td>
<td>1.1829</td>
<td>-0.0301</td>
</tr>
<tr>
<td>$\chi_3$</td>
<td>0.5613</td>
<td>0.4237</td>
<td>0.5525</td>
<td>-0.5638</td>
</tr>
<tr>
<td>$\chi_4$</td>
<td>1.7668</td>
<td>1.4898</td>
<td>1.2645</td>
<td>-0.5344</td>
</tr>
<tr>
<td>$\chi_5$</td>
<td>0.6666</td>
<td>0.5082</td>
<td>0.7275</td>
<td>6.361</td>
</tr>
</tbody>
</table>

Equation (14) is evidenced by the very fine agreement between the data points and the solid-line curves seen in figure 1.

**Results**

The agreement between the fitted approximation using equation (14) and the output from the numerical quadrature used to evaluate the integral of equation (13) is found to be extremely accurate for a wide range of proton energies relevant to cosmic-ray interactions.

A final interesting point in regard to Nagamiya and Gyulassy's representation (ref. 13) of the maximum transferable momentum (eqs. (10) and (12)) is that the representation involves a square root that allows a lower bound to be set on $T_{lab}$ below which the root becomes imaginary. Because the only variables besides $T_{lab}$ that are involved in the square root are the masses of the particles (ref. 14), the following lower limits on $T_{lab}$ are obtained for meson production in proton-proton collisions. Thus, for pions,

$$T_{lab} > 0.29 \text{ GeV}$$

and for kaons,

$$T_{lab} > 1.12 \text{ GeV}$$

which are just the threshold energies.

**Concluding Remarks**

A parameterization of the energy-differential cross sections for charged pion and kaon production from proton-proton collisions has been derived that accurately reproduces results obtained by numerically integrating the Lorentz-invariant cross section. Because the parameterization is simply a function of incident proton kinetic energy and outgoing meson parallel momentum, the results can be easily reproduced and should be very useful in computer transport codes that have not yet been tested with meson cross sections.

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Appendix A

Proofs of Formulas Used in Text

**Mandelstam Energy Variable**

The Mandelstam energy variable \( s \) for the reaction \( A + B \rightarrow C + D \) by definition, is given as

\[
\frac{s}{c^2} = \frac{(p_A + p_B)^2}{c^2}
\]

In lab frame, \( p_B = 0 \) and \( E_B = m_Bc^2 \). Thus, \( s \) is expressed as

\[
s = \frac{(p_A^2 + p_B^2 + 2p_Ap_B)}{c^2} = \frac{m_A^2 + m_B^2 + (2/c^2)p_Ap_B}{c^2} = \frac{m_A^2 + m_B^2 + (2/c^2)(E_A/c, p_A) \cdot (E_B/c, p_B)}{c^2} = \frac{m_B^2 + m_B^2 + (2/c^2)(E_A/c, p_A) \cdot (m_B/c, 0)}{c^2} = \frac{m_A^2 + m_B^2 + (2E_Am_B/c^2)}{c^2}
\]

**Maximum Transferable Momentum**

The maximum transferable momentum for the reaction \( A + B \rightarrow C + D \) in the center-of-mass frame where \( p = p_A = -p_B \) and \( q = p_c = -p_D \), is given by

\[
q_{\text{max}} = \left[ \left( s - m_C^2c^4 - M^2c^4 \right)^2 - 4m_C^2M^2c^4 \right]^{1/2}/2cs^{1/2}
\]

where

\[
M = m_A + m_B
\]

Here, \( s \) is defined as

\[
s = \frac{(p_A + p_B)^2}{c^2} = \frac{(p_C + p_D)^2}{c^2} = \frac{(E_C/c, q) + (E_D/c, -q)}{c^2} = \frac{(E_C/c) + (E_D/c, 0)}{c^2} = \frac{(E_C + E_D)^2}{c^2}
\]

which yields

\[
E_C + E_D = s^{1/2}
\]

When relating energy and momentum via

\[
E_C^2 = q^2c^2 + m_C^2c^4
\]

\[
E_D^2 = (-q)^2c^2 + m_D^2c^4
\]

the difference between \( E_C^2 \) and \( E_D^2 \) is given as

\[
E_C^2 - E_D^2 = (m_C^2 - m_D^2)c^4
\]

Now, since

\[
E_C^2 - E_D^2 = (E_C + E_D)(E_C - E_D)
\]

we have

\[
E_C - E_D = (m_C^2 - m_D^2)c^4/(E_C + E_D)
\]

where \( E_C + E_D \) is given by equation (A1). Hence,

\[
E_C - E_D = (m_C^2 - m_D^2)c^4/2s^{1/2}
\]

**Spectral Distribution**

The spectral distribution is given as

\[
\frac{d\sigma}{dE} = \frac{\pi}{c^2 p_{\parallel}} \int \frac{E}{d^3p} \frac{d^3\sigma}{dp_{\parallel} dp_{\perp} d\theta}
\]

For proof, we let

\[
\frac{E}{d^3\sigma}{d^3p} = \frac{E}{d^3\sigma}{d^3p_{\parallel} d^3p_{\perp} d\theta}
\]

Integrating with respect to \( \theta \) gives

\[
2\pi \frac{E}{d^3\sigma}{d^3p} = \frac{E}{d^3\sigma}{d^3p_{\parallel} d^3p_{\perp}}
\]

We can simplify further via

\[
p_{\perp}^2 = p_{\parallel}^2 + p_{\perp}^2
\]

\[
E = \left[ (p_{\perp}^2 + p_{\parallel}^2)c^2 + m_D^2c^4 \right]^{1/2}
\]

\[
\frac{dE}{dp_{\parallel}} = \frac{p_{\parallel}c^2}{E}
\]

\[
\frac{dp_{\parallel}}{p_{\parallel}c^2} = \frac{dE}{E}
\]

(A5)
and

\[
d(p^2_{\perp}) = 2p_{\perp} dp_{\perp}
\]

\[
p_{\perp} dp_{\perp} = d(p^2_{\perp})/2 \quad \text{(A6)}
\]

Substituting equations (A5) and (A6) into the denominator on the left-hand side of equation (A4) gives

\[
2\pi \frac{E d^3 \sigma}{d^3 p} = \frac{E d^2 \sigma}{d(p^2_{\perp})/2}
\]

and

\[
\frac{\pi}{c^2 p_{\parallel}} \frac{E d^3 \sigma}{d^3 p} = \frac{d^2 \sigma}{d(p^2_{\perp})} \quad \text{(A7)}
\]

Finally, integrating with respect to \( p^2_{\perp} \) yields the desired result

\[
d\sigma = \frac{\pi}{c^2 p_{\parallel}} \int \frac{E d^3 \sigma}{d^3 p} d(p^2_{\perp}) \quad \text{(A8)}
\]

which allows us to isolate \( E_C, E_D, \) and \( q \) in terms of \( m_C, m_D, \) and \( s \) as

\[
E_C = \left[ s + (m_C^2 - m_D^2) c^2 \right]^{2^{1/2}}
\]

\[
E_D = \left[ s + (m_C^2 - m_D^2) c^2 \right]^{2^{1/2}}
\]

\[
q^2 = (E_C/c^2) - m_D^2 c^2 = \left\{ \left[ \left( s + (m_C^2 - m_D^2) c^2 \right)^{2^{1/2}} \right] c^2 \right\} - m_D^2 c^2
\]

\[
= \left[ s + (m_C^2 - m_D^2) c^2 \right]^{2^{1/2}} - 4s m_C^2 c^4 /4s c^2
\]

\[
= \left[ s + 2s (m_C^2 - m_D^2) c^4 + (m_C^2 - m_D^2) c^8 - 4m_C^2 c^4 \right] /4s c^2
\]

\[
= \left[ s + 2s (m_C^2 + m_D^2) c^4 + (m_C^2 - m_D^2) c^8 \right] /4s c^2
\]

Note that \( q \) is the transferred momentum and that for given particles \( A, B, \) and \( C \) and given incident energy \( E_{\text{beam}} \), the only variable left in \( q \) is \( m_D \), which can be no larger than \( m_A + m_B \). Hence, the maximum transferable momentum is given as

\[
q_{\text{max}} = \left\{ s^2 - 2sc^4 (m_C^2 + (m_A + m_B)^2) \right\}^{1/2} /2cs^{1/2}
\]

and if we let \( M = m_A + m_B \), the result is

\[
q_{\text{max}} = \left[ s^2 - 2sc^4 (m_C^2 + M^2) \right]^{1/2} /2cs^{1/2}
\]

\[
= \left[ (s^2 - m_C^2 c^4 - M^2 c^8)^2 - 4m_C^2 c^8 \right] /2cs^{1/2}
\]

which is the desired result.
Appendix B

Computer Program of Spectral Parameterizations

The following computer program utilizes the parameterization given by Badhwar, Golden, and Stephens, (ref. 11) to plot a graph of the spectral distribution. The integration is performed by using adaptive Gaussian 32-point quadrature to find the integral.

The program is written in FORTRAN-77, which does not support the many fonts found in this paper; hence, naming the variables can become quite tedious. A complete list of the meaning of all the variables found in the main procedure is given as follows:

A, B, C, C1, C2, C3 parameterization constants ($A_1, A_2, C, C_1, C_2,  C_3$, respectively) from table 1
dppar dummy variable used to vary pparcm inside loop
dsdE $= d\sigma/dE$, energy-differential cross section
e total energy of incoming proton
fac represents one part of equation (1) that does not vary with respect to $p_\parallel$ or $p_\perp$
intgrl value of actual definite integral
invcs value of invariant cross section, returned by function of same name
mkaon mass of kaon
mp mass of proton
mpion mass of pion
particle determines which particle the program will investigate
pcmax maximum transferable momentum
pparcm $= p_\perp$, perpendicular component of c.m. momentum
pparcm $= p_\parallel$, parallel component of c.m. momentum
q $= q, \text{ from equation (5)}$
R $= \gamma, \text{ parameterization constant from table 1}$
s Mandelstam energy
Tlab kinetic energy of incident proton
x $= 1 - xtilde, \text{ as seen in equations (3)}$ and (4)
\xparsq $= x_{\parallel}^2, \text{ from equation (3)}$
xtilde scaling variable found in equation (3)
IMPLICIT DOUBLE PRECISION (a-z)
INTEGER particle
COMMON mass,A,B,C1,C2,C3,R,q,s,particle,fac,xparsq

* mass of proton in GeV/c**2
mp = .93827231
* mass of pion in GeV/c**2
mpion = .1395679
* mass of kaon in GeV/c**2
mkaon = .493646
pi = 3.141592653589793238

do 2000 Tlab = 10.
do 1000 particle = 1,4,1

IF (particle.EQ.1) THEN
  for positive pion...
  A = 153.
  B = 5.55
  R = 1.
  C1 = 5.3667
  C2 = -3.5
  C3 = 0.8334
  mass = mpion
  open(50, file='intpp0010.dat')
ELSEIF (particle.eq.2) then
  for negative pion...
  A = 127.
  B = 5.3
  R = 3.
  C1 = 7.0334
  C2 = -4.5
  C3 = 1.667
  mass = mpion
  open(50, file='intnp0010.dat')
ELSEIF (particle.eq.3) then
  for positive kaon...
  A = 8.85
  B = 4.05
  C = 2.5
  mass = mkaon
  open(50, file='intpk0010.dat')
ELSEIF (particle.eq.4) THEN
  for negative kaon...
  A = 9.3
  B = 3.8
  C = 8.3
  mass = mkaon
  open(50, file='intnk0010.dat')
Mandelstam energy
\[ e = \frac{T_{lab}}{m_p} \]
\[ s = 2.\times(m_p^2) + 2.\times e^2 \]

maximum transferable momentum
\[ p_{cmmax} = \sqrt{((s - m_s^2) - 4.\times(m_p^2))^2 - 16.\times(m_s^2)\times(m_p^2)/(4.\times s)} \]
write(6,*) particle, T_{lab}, e, s, ' p_{cmmax} = ', p_{cmmax}

(neither perpendicular nor parallel component can be greater than p_{cmmax}.)
(lower limit on integral is 0. Upper limit is p_{cmmax}^2, since we're integrating with respect to the square of the perpendicular momentum, and changed variables)
'fac' is a COMMON variable, and is used in invcs:
fac = 1. + 4.\times(m_p^2)/s
d_{pp} = p_{cmmax}/1000.
p_{parc} = 0.
do 10 p_{parc}=0., p_{cmmax}, d_{pp}
x_{parsq} = (p_{parc}/p_{cmmax})^2

intgrl = AdaptiveGauss(DFLOAT(0), p_{cmmax}^2)

IF (intgrl.GE.0.) THEN
d_{sdE} = (pi/p_{parc})\times intgrl
write(50,*) p_{parc}, d_{sdE}
ELSE
write(6,*) 'did not work:', p_{parc}, intgrl
ENDIF
10 continue
close(50)

1000 continue
2000 continue

stop
end

Adaptive Gaussian Quadrature...
sent in: lower and upper integration limits (p_{parc} limits)
returns the integral approximation 'Approx' of integral of Lorentz invariant cross section (invcs).

DOUBLE PRECISION FUNCTION AdaptiveGauss(Qlim, Qlim)
IMPLICIT DOUBLE PRECISION (a-z)
INTEGER z, particle
COMMON mass, A, B, C1, C2, C3, R, q, s, particle, fac, xpar sq

DIMENSION low(1000)
DIMENSION mid(1000)
DIMENSION upp(1000)
DIMENSION sum(1000)
DIMENSION tol(1000)
DIMENSION sav(5)

Approx = 0.
z = 1
tol(z) = 1. / (10. ** 10)
low(z) = llim
mid(z) = (llim + ulim) / 2.
upp(z) = ulim
sum(z) = Gauss32(low(z), upp(z))

100 IF (z .GT. 0) THEN
   s1 = Gauss32(low(z), mid(z))
   s2 = Gauss32(mid(z), upp(z))
   sav(1) = low(z)
   sav(2) = mid(z)
   sav(3) = upp(z)
   sav(4) = tol(z)
   sav(5) = sum(z)
   z = z - 1
   IF (DABS(s1 + s2 - sav(5)).LT.sav(4)) THEN
      Approx = Approx + (s1 + s2)
   ELSE
      IF (z .GE. 999) THEN
         AdaptiveGauss = -1.
         goto 9999
      ELSE
         * calculate for right-hand side subinterval:
         z = z + 1
         low(z) = sav(2)
         upp(z) = sav(3)
         mid(z) = (low(z) + upp(z)) / 2.
         tol(z) = sav(4) / 2.
         sum(z) = Gauss32(low(z), upp(z))
      * calculate for left-hand side subinterval:
         z = z + 1
         low(z) = sav(1)
         upp(z) = sav(2)
         mid(z) = (low(z) + upp(z)) / 2.
```fortran

tol(z) = tol(z-1)
sum(z) = Gauss32(low(z),upp(z))

ENDIF
ENDIF
GOTO 100
ENDIF
AdaptiveGauss = Approx

9999 return
end

******************************************************************************
* 32-point Gaussian Quadrature, used in conjunction w/ AdaptiveQuad above   *
******************************************************************************

DOUBLE PRECISION FUNCTION Gauss32(llim,ulim)
Implicit Double Precision (a-z)
Integer i,degree
Dimension Wgt(32), Zero(32)

degree = 32
CALL LEGEND(Wgt, Zero)

sum = 0.0
DO 300 i=1,degree
   x = (Zero(i)*(ulim - llim) + llim + ulim)/2.
   NewWgt = Wgt(i)*(ulim - llim)/2.
   sum = sum + invcs(x)*NewWgt

300 CONTINUE
Gauss32 = sum
RETURN
END

******************************************************************************
* Lorentz-invariant cross section of DSQRT(temp)....                           *
******************************************************************************

DOUBLE PRECISION FUNCTION invcs(temp)
   IMPLICIT DOUBLE PRECISION (a-z)
   INTEGER particle
   COMMON mass,A,B,C,C1,C2,C3,R,q,s,particle,fac,xparsq
   ppercm = DSQRT(temp)

   xtilde = DSQRT(xparsq + 4.*(ppercm**2 + mass**2)/s)
   x = 1. - xtilde
   if (x.GE.0.) then
      if (particle.LT.3) then
         q = (C1 + C2*ppercm + C3*(ppercm**2))/DSQRT(fac)
         invcs = A/(fac**(R))*x**q*DEXP(-B*ppercm/fac)
      else
         invcs = A*(x**(C))*DEXP(-B*ppercm)
      endif
   else
      invcs = A*(x**(C))*DEXP(-B*ppercm)
   endif
end
```
invcs = 0.
endif
return
end

*---------------------------------------------------------------*
  Legend: Set initial values for Laguerre Weights and Points....
*---------------------------------------------------------------*
SUBROUTINE LEGEND(WL, P)
  Implicit Double Precision (A-H,M,O-Z)
  Dimension WL(96), P(96)
  Laguerre weights are WL, Laguerre points are P
  WL( 1)= 0.701861000947001211890811321403D-02
  WL( 2)= 0.16274394739056608344079997153D-01
  WL( 3)= 0.253920653092620713688065681168D-01
  WL( 4)= 0.342738629130214167081702747453D-01
  WL( 5)= 0.428358980222266422580035261092D-01
  WL( 6)= 0.509980592623762328183256720138D-01
  WL( 7)= 0.586840934785355676159279703086D-01
  WL( 8)= 0.6582222776361790502752668855D-01
  WL( 9)= 0.723457941088485479569358815866D-01
  WL(10)= 0.781938957870702434221898968758D-01
  WL(11)= 0.83311924269647676770267061670D-01
  WL(12)= 0.876520930044039341816342059133D-01
  WL(13)= 0.911738786957638977503926014379D-01
  WL(14)= 0.9384439908080452474870001461195D-01
  WL(15)= 0.956387200792749008620985406992D-01
  WL(16)= 0.965400885147278502163015190263D-01
  WL(17)= 0.96540088514727810317661575597D-01
  WL(18)= 0.95638720079274919944056776441D-01
  WL(19)= 0.9384439908080464627098965125424D-01
  WL(20)= 0.911738786957639324448621209740D-01
  WL(21)= 0.876520930044038994871666863771D-01
  WL(22)= 0.83311924269647616561745665149D-01
  WL(23)= 0.781938957870701180152993638785D-01
  WL(24)= 0.7234579410884864826210160391869D-01
  WL(25)= 0.658222227763619171375664151924D-01
  WL(26)= 0.5868409347853556109840148697288D-01
  WL(27)= 0.5099805926237615735785446702277D-01
  WL(28)= 0.428358980222266422580035261092D-01
  WL(29)= 0.342738629130214167081702747453D-01
  WL(30)= 0.253920653092620713688065681168D-01
  WL(31)= 0.16274394739056608344079997153D-01
  WL(32)= 0.701861000947001211890811321403D-02
  P( 1)= -0.997263681849481667021244390980D+00
  P( 2)= -0.985611511545268423238813867101D+00
  P( 3)= -0.964762255587506528664576421761D+00
  P( 4)= -0.934906075937739761914713364557D+00
  P( 5)= -0.896321155766052188318404603251D+00
P(  6) = -0.849367613732570012063938236224D+00
P(  7) = -0.79448379596794242441063058822692D+00
P(  8) = -0.7321821187402897113111675091565D+00
P(  9) = -0.6630442669302152453303692483958D+00
P( 10) = -0.58775157572407624291921179722223D+00
P( 11) = -0.506899908932229414926240451678D+00
P( 12) = -0.421351276130635395145151989027D+00
P( 13) = -0.3316866022821276671024293113672D+00
P( 14) = -0.23928736225213704391497535552D+00
P( 15) = -0.144471961582796494527602959579D+00
P( 16) = -0.483076656877383025720518183732D-01
P( 17) =  0.483076656877383077762222463036D-01
P( 18) =  0.144471961582796480649815151764D+00
P( 19) =  0.239287362252137043860944487506D+00
P( 20) =  0.3316866022821276671024293113672D+00
P( 21) =  0.421351276130635395145151989027D+00
P( 22) =  0.506899908932229414926240451678D+00
P( 23) =  0.587751575724076234592541112533D+00
P( 24) =  0.6630442669302152453303692483958D+00
P( 25) =  0.7321821187402897113111675091565D+00
P( 26) =  0.79448379596794242441063058822692D+00
P( 27) =  0.849367613732570012063938236224D+00
P( 28) =  0.896321155766052146685041117908D+00
P( 29) =  0.934906075937739763914713364557D+00
P( 30) =  0.964762255587506459275637382689D+00
P( 31) =  0.985611511545268367817662635844D+00
P( 32) =  0.997263861849481611510093159723D+00

return
end
References


Figure 1. Spectral distribution $d\sigma/dE$ plotted against parallel component of outgoing meson momentum. Data points denote actual values obtained by performing numerical quadrature on integral portion of equation (13); solid-line curves denote the fit approximation of equation (14).
Figure 1. Concluded.

(c) Positive kaon production.

(d) Negative kaon production.
Parameterized Spectral Distributions for Meson Production in Proton-Proton Collisions

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Accurate semiempirical parameterizations of the energy-differential cross sections for charged pion and kaon production from proton-proton collisions are presented at energies relevant to cosmic rays. The parameterizations, which depend on both the outgoing meson parallel momentum and the incident proton kinetic energy, are able to be reduced to very simple analytical formulas suitable for cosmic ray transport through spacecraft walls, interstellar space, the atmosphere, and meteorites.