The results obtained in the framework of the NA63 experiment at CERN are reported. Trident production in the strong crystalline fields of single Ge crystals are enhanced by about a factor 3 compared to a Ge amorphous material. Formation lengths of several microns for the production of GeV photons from ultrarelativistic electrons is directly observed in structured targets, and a new technology to generate oscillating planes in diamond, suitable for a crystalline undulator is presented. The plans for 2008 include a measurement of resonance phenomena in structured targets and a possible change in restricted energy loss in thin solid state detectors, for sufficiently high values of the Lorentz factor.
Figure 1: The CCD detector and the thin gold foil used for the measurements of the Chudakov effect. Cooling of the detector was performed through thermal contact of the Cu-blocks shown, to a \( \text{IN}_2 \) reservoir. The size of the sensitive area of the detector is 12.7 mm \( \times \) 12.7 mm.

1 Introduction

As part of the fixed-target programme at the SPS, NA63 was given 3 weeks of beamtime in H4 in 2007. Furthermore, during the time since the first presentation at the Villars meeting in 2004 of the ideas that eventually lead to the proposal [1], the participants of the NA63 collaboration have taken advantage of a number of test-beam periods, resulting in a total of 10 publications related to the NA63 activities since 2004.

One recent development deserves mentioning: A new approach to measuring the so-called Chudakov effect. The Chudakov effect is a decrease in restricted energy loss close to the vertex of a pair due to the internal screening of the charges constituting the pair. In the preparatory phase of the NA63 experiment - that is, with essentially the same team, but in a test beam allocated in 2004 - we performed the first measurement of the Chudakov effect in an accelerator environment. The technique was based on the detection of a reduced restricted energy loss in a \( \text{IN}_2 \)-cooled CCD detector, shown in figure 1, with the pairs produced in a thin gold foil positioned at a known distance. The paper is scheduled for publication in Phys. Rev. Lett. in the 02 May issue [2].

2 Results from the run, Oct. 2007

In 2007, NA63 investigated 4 phenomena:

1. Trident production in strong crystalline fields
2. Pair production in strong crystalline fields
3. Formation length effects in structured (sandwich) targets
4. Crystalline undulator radiation from laser-ablated diamonds

See [3, 4, 5] for reviews of similar effects in strong crystalline fields.

2.1 Trident production in strong crystalline fields

In effect, this is an investigation of the so-called Klein paradox, where an electron impinging on a sufficiently steep potential barrier, gives rise to direct pair production, i.e. in total three charged particles are emerging, see e.g. [6, 7, 8]. In this connection, 'sufficiently steep' means of the order the QED critical field, \( \mathcal{E}_0 = mc^2/e\lambda_c = 1.32 \times 10^{16} \text{ V/cm} \), i.e. the rest mass of the electron can be produced by transporting an electron over the distance corresponding to the uncertainty of the location of it, the reduced Compton wavelength \( \lambda_c = \hbar/mc \). Such fields as \( \mathcal{E}_0 \) are achievable in the rest frame of the penetrating particle, taking advantage of the Lorentz boost and the coherent addition of the screened nuclear fields in crystals, leading to electric fields of magnitude \( 10^{11} - 10^{12} \text{ V/cm} \). More compactly, the relativistic invariance of the parameter

\[
\chi = \gamma \mathcal{E} / \mathcal{E}_0
\]

is taken advantage of. Using a Weizsäcker-Williams approach of equivalent photons, one can therefore expect a significant enhancement in the yield of trident events in crystals, compared to the same amor-
Figure 2: The setup used by NA63 for the investigation of trident production in strong crystalline fields

Figure 3: Enhancement differential in the energy of the produced electron from trident events in 400 micron thick Ge \(< 110\rangle\) (filled squares) and 170 micron thick Ge \(< 110\rangle\) (filled circles)

In figure 2 is shown a schematical drawing of the setup used. The electron beam, incident from the left is analyzed in two drift chambers (DC1, DC3) to give accurate information on the entrance position and angle on the target. Right after the target, a solid state detector, SSD, counts the number of particles emerging from the target. Finally, in the case of trident production, the low energy pair is momentum (MDX, DC5, DC6) and energy analyzed (ScJ, ScS and the respective E.M. CALORIMETERS), whereas the primary particle - having lost little energy to the created pair - is hardly deflected in the MDX and continues to the downstream lead glass. The system is therefore optimized for the detection of low energy pairs created in the trident process - the situation where the enhancement is expected to be strong, and the likelihood of the process proceeding through a virtual intermediate photon is high.

A preliminary analysis of the data obtained in the experiment shows an enhancement of about a factor 3 in 0.4 mm Ge for 125 and 180 GeV electrons, and slightly higher for 210 GeV electrons. Preliminary results for two target thicknesses with 180 GeV electrons are shown in figure 3. For a calculation of enhancements in crystals, see [9].

As seen from the figure, the enhancement is hardly affected by the thickness of the target. In the case of the process proceeding through a virtual intermediate photon, the trident rate scales linearly with thickness, whereas for the real photon intermediate stage, it scales with the square of the thickness. For the amorphous case, the expected ratio of virtual to real intermediate rate is about 600 to 1, so in that case the trident process through a virtual intermediate photon is by far the dominating [10]. The enhancement - ratio of crystalline to amorphous rates - being almost independent of thickness means that the processes must scale equally with thickness, i.e. the strong field contribution is likely to be through a virtual intermediate photon, direct trident.

Analysis is at the time of writing in the final stage, expected to be completed by autumn 2008.
Figure 4: Enhancement of the Ta5Al6 sandwich target compared to the 100 micron thick Ta reference target. The filled squares represent the measured values, the solid line a result based on a theory by Blankenbecler [13] for the target acting as 20 separate entities, the dashed line shows the resonance obtained from 2 foils and the dotted line shows the full target configuration. Finally, an alternative theory by Shul’ga and Fomin is shown as a dash-dotted line [12].

2.2 Pair production in strong crystalline fields

Recent studies have shown that it may be possible to detect the LPM effect in pair production [11], i.e. that the yield of pair production events may be suppressed by multiple scattering of the virtual pair. In NA63 we have performed in 2007 a precise measurement of the pair production from 2-100 GeV photons in a Ge crystal, to address this question. Once the trident analysis has been completed, we expect to analyze this data-set.

2.3 Formation length effects in structured (sandwich) targets

By assembling a target of tantalum sub-targets, interspersed with aluminum spacers for which the radiation length is significantly smaller, so-called structured target phenomena can be investigated. These phenomena arise due to the large longitudinal extent of the formation zone,

\[ l_f = \frac{2\gamma^2c}{\omega} \]  

an extent that for sufficiently high electron energies and sufficiently small photon energies, may exceed the dimension of the tantalum sub-targets, or span across the aluminum spacers. This leads to suppression or enhancement, depending on photon energies.

In 2007, NA63 investigated such effects with beam energies of 206 and 234 GeV, and various target configurations. Ta targets of thicknesses in the range 5-10 microns and with Al spacers 6-12.5 microns were used. In figure 4 is shown the result obtained with a target composed of 20 layers of 5 micron Ta interspersed with 6 microns of Al. As seen from the figure, the enhancement at low photon energies - where the formation length of the photon extends out of each target segment - is in good agreement with the theoretical curve obtained on the basis of the theory of Blankenbecler [13]. On the other hand, there is no sign of the resonances arising from the formation length extending across the gap between two Ta foils. This absence is most likely due to insufficient compression of the sandwich target, leading to larger-than-expected gaps. Nevertheless, the increase observed at low photon energies can be readily interpreted as a measurement of the formation length of 10 GeV photons being of about 5 micron size: It takes the electron a length of travel of several microns to produce a GeV photon, even though the wavelength of the photon is 10 orders of magnitude smaller.
2.4 Crystalline undulator radiation from laser-ablated diamonds

The possibility of obtaining undulator-like radiation from a suitably oscillating periodic lattice in a crystal has been investigated in 2007. In particular, NA63 has refined the technology to obtain the required lattice distortions, such that using femto-second laser-ablation it is now possible to construct a diamond crystal with interlaced surface grooves, shown in figure 5, imposing strain that penetrates to the bulk of the crystal [15].

A channeled positron in such a lattice could yield radiation of the undulator type, but in the MeV region instead of the eV-keV region, simply because the wavelength in the solid-state undulator can be made much shorter, of the order 50 microns. This type of radiation, achievable due to the strong electric fields near the screened nuclei in the crystal lattice, may eventually lead to stimulated emission in the MeV region, a gamma-ray laser. Furthermore, we have developed technology to produce strained layer superlattice crystals consisting of silicon with varying content of germanium, again imposing the desired strain to get an oscillating behaviour of the crystal lattice.

3 Plans for the run, Oct. 2008

Given the tight financial constraints imposed by a severe and unexpected budget cut by more than 50% in 2008, the planned setup for NA63 is not within its financial capabilities. It is expected that the planned programme can be funded and completed in 2009. Instead, in 2008 we plan to use the allocated 2 weeks of beam time in H4 for studies of two effects that only require a reduced setup, i.e. one without drift chambers. Including drift chambers in the setup is time- and manpower consuming - and therefore relatively costly - due among other things to the thorough safety procedures to be followed using flammable gases. The two planned activities are:

1. Sandwich target studies
2. A study of the 'Ogle effect'

3.1 Sandwich target studies

Although the studies during the 2007 beam time were succesful in measuring the macroscopic formation length of photons from ultrarelativistic electrons, the resonances predicted to arise when the formation length extends across the gap between the Ta sub-targets were not observed. To enlarge the region of interest for photon energies substantially, we have acquired a new BGO detector of 75 mm (Ø) × 200 mm. This detector has an acceptable efficiency for the detection of photons in the region between about 50 MeV and 5 GeV (simulated by use of GEANT), providing an overlap with the efficient region of the lead glass detectors that extend down to about 2 GeV. By use of the BGO detector, we expect to be able to detect the predicted resonances, as the difference between the full sandwich target and the configuration where each sub-target acts independently becomes large at low photon energies as shown in figure 6. The setup requires only 3 scintillator counters for the beam definition, an MBPL magnet and the BGO and lead glass detectors.
Figure 6: As figure ??, but on a logarithmic photon energy scale, showing the range of interest available with the acquired BGO detector.

3.2 A study of the 'Ogle effect'

In a measurement performed 30 years ago, Ogle and collaborators [18] investigated a reduction in energy deposition in a thin solid state detector, 100 µm of Si. They reported a reduction in restricted energy loss for values of the Lorentz factor exceeding

\[ \gamma_c = \frac{a\omega_p}{2c} \]  

based on four data points in the region \( \gamma \in [1.6 \cdot 10^4; 1.0 \cdot 10^5] \), where \( \gamma_c = 7.9 \cdot 10^3 \). In equation (3) \( a \) is the thickness of the detector and \( \omega_p \) the plasma frequency. Their theoretical approach was based on an argument with minimum longitudinal momentum transfer, similar to studies of the formation zone as discussed above. Although their theory is questionable, it seems to be supported by the measured values.

On the other hand, one can use a characteristic length for the generation of transition radiation as e.g. defined in [16] or [17]

\[ l_c = \frac{2\gamma^2 c}{\omega} = \frac{2\gamma c}{\omega_p} \]  

with \( \omega = \gamma \omega_p \). From equation (4) appears that the full screening of the field of the penetrating particle takes place only after a distance \( l_c \), i.e. for distances shorter than this the density effect may not be fully active for the restricted energy loss. This would result in an increased energy deposition for values of the Lorentz factor exceeding that given in equation (3).

We plan to study this decreased, perhaps increased, energy deposition in thin solid state detectors for \( \gamma > \gamma_c = 7.9 \cdot 10^3 \), corresponding to energies above 4 GeV. Using an electron beam of energy 200 GeV passing a target of 1 \( X_0 \) and being deflected in an MBPL magnet, we can generate electrons of energies in the interval between about 0.5 GeV and 200 GeV, equivalent to \( \gamma \in [1.0 \cdot 10^3; 3.9 \cdot 10^5] \), tagged by means of the signal in the lead glass detector. By moving the thin solid state detector stepwise across the deflected electron beam, we can obtain a full spectrum of about 50 energy points in a few days of beam time.
References