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Status and plans for 2015, CERN NA63

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NA63

Abstract

We summarize the status and plans for the future for the CERN NA63 collaboration. A systematic study of the structured target ‘resonance’ appearing from radiation emission by electrons passing two amorphous foils positioned with separations in the range $10^{-20000} \mu m$ was performed in our latest run. The recently published results [1] confirm a previously obtained result [2] that by this method, the formation length - of macroscopic dimensions up to $0.5 \text{ mm}$ - for the generation of MeV-GeV radiation from multi-hundred GeV electrons can be directly measured. In fact the results obtained now allow a distinction between competing theories [3, 4], showing that it is unlikely that the correction-term introduced by Blankenbecler holds true [5].

Our investigations of the LPM effect in low-Z targets have been completed and published [6]. The overall conclusion for these studies is that the formalism of Migdal is sufficient to describe the experimental data - for any $Z$ - within the statistical uncertainty.

Preparing for beam time in 2015, we have refined and updated our theoretical analyses of bremsstrahlung and delta-electron emission from heavy, and medium-heavy, ultrarelativistic nuclei. We can thus conclude that - although not quite as interesting as for Pb projectiles - projectiles of Ar and/or Xe are suitable for the investigation, and for establishing the method to eventually measure the charge distribution of short-lived ($ct \gtrsim 3m$) fragments [7].

Furthermore, we have prepared a new simulation code to determine the theoretically expected number of positrons produced by electrons traversing an aligned diamond target. This code, in a previous version, compares very well to radiation emission observed from sub-GeV electrons passing a crystalline undulator [8] - previously also the subject of investigations by CERN NA63.

1) On behalf of the collaboration.
1 Structured target 'resonances'

1.1 2012 measurement

In 2012 we performed an extensive investigation of the structured target resonances to investigate the significance of a theoretically expected correlation term (between phase and amplitude) and to obtain an accurate description of radiation emission in the presence of multiple scattering.

In a naïve approach, the resonance (or, rather, the lack of destructive interference) appears when the formation length

\[ l_f = \frac{2E(E - \hbar \omega)}{m^2 c^3 \omega} \approx \frac{2\gamma^2 c}{\omega^*} \quad \omega^* = \frac{E}{E - \hbar \omega}, \]

extends across the separation gap between two closely positioned foils. Thus, when the formation length equals the target spacing or gap width \( \delta g \) it leads to a resonance at a photon energy

\[ \hbar \omega < \hbar \omega_r = \frac{E}{1 + \frac{\delta g}{2\gamma \lambda_c}}, \]

Other effects involving the concept of formation length may be found in [9, 10].

In order to avoid cancellation of the sought-for effect, associated with stacks of foils, we measured with only two foils, mounted on a precisely controlled translation stage, such that the internal separation between the two foils could be controlled with an accuracy of a few microns. The resulting thickness limitation for the target foils sets rather severe constraints on the amount of extra material in the beam, e.g. from thin trigger scintillators, vacuum-pipe windows and beam-line diagnostics such as wire-chambers. Furthermore, the requirement of measuring photon energies down to a few tens of MeV imposes constraints on the magnetic field applied to deflect the electron from its radiated photon, due to the emission of typically several synchrotron radiation photons. To obtain a gentle deflection, i.e. a low field, two 2 meter long magnetic dipoles were run in series at a fairly low field, 0.17 T, giving a synchrotron radiation critical energy of \( \hbar \omega_c = 3\gamma^3 e\hbar B/2p \approx 3.6 \text{ MeV} \). Even with pile-up originating from several synchrotron radiation photons being emitted simultaneously, this allows detection down to \( \approx 30 \text{ MeV} \), without the need for deconvolution. Nevertheless, due to 'back-splash' from the lead glass calorimeter used to measure the energy of the electron, into the BGO calorimeter used to measure the energy of the photon, the lower detection limit was increased to \( \approx 50 \text{ MeV} \), and the efficiency of the BGO found from reference measurements is considered reliable only above \( \approx 100 \text{ MeV} \).

Figure 1: The final result for our measurements of the structured target 'resonances'. Shown as triangles with error bars is the location of the structured target 'resonance' peak, obtained with 178 GeV electrons passing 2 foils of each 26 micron thick gold, at separations of nominally 60, 100, 200 and 500 µm. The data is compared to several theoretical approaches which differ significantly. For details, please see our original paper, ref. [1].
In figure 1 is shown our measurements of the structured target 'resonance', where distances 10 (which shows no clear peak), 60, 100, 200, 500 and 20,000 (used as a reference) µm between the foils, have been investigated. With this method, we have determined the variation of the peak energy with foil separation: essentially a direct measurement of the formation length variation with photon energy.

The results were published recently in Physics Letters B [1].
2. Landau-Pomeranchuk-Migdal effect for low-Z targets

The Landau-Pomeranchuk-Migdal (LPM) effect was investigated experimentally in the mid-90s with 25 GeV electrons at SLAC [11] and later with up to 287 GeV electrons at CERN [12, 13]. These investigations - combined with relevant theoretical developments - have shown that the theory of multiple scattering dominated radiation emission is describing experiment very well, at least for high-Z targets.

In his review paper on the LPM effect from 1999 [14], Spencer Klein stated among the explanations for a small, but significant, discrepancy found for carbon with electrons at 25 GeV that “‘it is also possible that Migdal’s theory may be inadequate for lighter targets.”’. Likewise, in the CERN experiments [13], where carbon was used as a calibration target, the (small) systematic deviations from the expected values for $E_{LPM}$ could possibly be explained by an insufficient theoretical description of carbon.

As described in [15], the most widely used theory for the LPM effect, developed by Migdal [17], potentially has at least two shortcomings: It is based on the Thomas-Fermi approximation, known to be inaccurate for atoms of low nuclear charge [17, eq. (22)]. Furthermore, for several combinations of electron energies and photon energies, the resulting spectra show what seems to be an unphysical ‘kink’ in the radiation spectrum. An example of such a ‘kink’ is shown in figure 3 (left).

The more modern theory by Baier and Katkov which includes Coulomb corrections and other fine details, is developed mainly for high-Z targets, and therefore does not include screening adequately for low-Z targets. The accuracy of their theory is expected to be a few percent for high-Z targets, whereas for low-Z targets the error may be as much as 10-15%.

Finally, the contribution from electrons may be influenced differently by the LPM effect than the nuclear contribution, resulting in another potential difference between the true multiple scattering effects in low-Z and high-Z targets.

The aim of our measurements in 2012 was to address these questions.

2.1 Measurements with electrons of 178 GeV

Figure 2: Examples of results for the low-Z LPM measurement performed with electrons of 178 GeV in $\approx 2.5\% \, X_0$ targets of LowDensityPolyEthylene (LDPE), Carbon, Aluminum, Titanium, Iron, Copper, Molybdenum and Tantalum. Adapted from [6].

In figure 2 is shown three examples of the results obtained from the measurements performed in LowDensityPolyEthylene (LDPE), Carbon, Aluminum, Titanium, Iron, Copper, Molybdenum and Tantalum targets. To an accuracy limited by the statistical uncertainty of the measurements, there is no reason to doubt the validity of Migdal’s formulation of the LPM suppression, even for low-Z targets.

2.2 Measurements with electrons of 20 GeV

In figure 3 is shown the results for the low-Z LPM measurement performed with electrons of 20 GeV in a $\approx 2.5\% \, X_0$ target of Copper. The presence of a ‘kink’ in the radiation spectrum - while clearly visible from the theory (left figure) - is not apparent from the experimental data (right figure). The main reason for this is the existence of events with pile-up, that contribute to a smearing out of the ‘kink’.

The results were published in Physical Review D [6].
3 Plans for 2015

4 Positron production by electrons in a diamond

In view of recent developments in the field of efficient positron production by use of crystalline targets [18, 19, 20, 21, 22], we have on previous occasions [15, 16] shortly described a possible study using diamond crystals. The relevance of such a study is high, as e.g. CLIC and LHeC $e^+e^-$-production schemes are expected to gain significantly (at least several tens of percent, perhaps even factors of 3-4) from using crystalline targets where the strong field effects - studied in detail experimentally by the NA43 and NA63 collaborations - play a decisive role. Due to the high power of the primary electron beam in such schemes, characteristics such as radiation hardness, melting point and thermal conductivity of the target are key elements. Diamond is unique in this respect, known to be superior to all other crystals, but clearly has the disadvantage of high cost, in particular for large specimens.

The production angles and energies can be measured by means of the so-called MIMOSA detectors [23] arranged in a magnetic spectrometer configuration with a permanent-magnet-based magnetic dipole that through a shunting mechanism has a variable field (the dipole is kindly provided on loan from DANFYSIK). The advantage of a permanent-magnet-based magnetic dipole is naturally its lack of power consumption that makes it possible with relative ease to install the entire spectrometer configuration in vacuum or a He-bag - no need for water cooling nor current supply. We plan to do this in future measurements, giving a significantly improved momentum resolution at the low pair energies (few tens of MeV) which are of main interest.

We have found that measurements using diamond have been performed, but with a somewhat different setup that only allows measurements at specifically chosen positron momenta and integrated over forward angles [24]. In those measurements the enhancement is high for diamond of small thicknesses, whereas for thicknesses large enough to yield an acceptable production rate the enhancement for diamond is smaller than for other crystals, and fairly rapidly approaches one, with increasing thickness. It must be emphasized, though, that the actual phase-space density has not been measured, the enhancement thus likely being a pessimistic number. Moreover, a systematic study of diamond as a primary radiation emitting target, and subsequent conversion in e.g. tungsten targets of different thicknesses, has not been performed.

As shown in figure 4 the positron yield is expected to increase drastically by simply turning the crystal from a non-aligned orientation, where the beam direction does not coincide with a low-index crystallographic direction, to an aligned orientation where they do coincide. A measurement of this enhancement, and the phase-space density of the emerging positrons, is the aim of the proposal for electrons in H4 in 2015.
4.1 Requested beam and beam time

We request 3 weeks of beam time in H4, with electrons of energies in the range 10 to 50 GeV. The beam needs to be fairly parallel (≈ 100 µrad) at the location of the crystal.
5 Nuclear-size effects in radiation emission

In previous addenda to our proposal [15, 16] we have proposed to measure the bremsstrahlung emission from \( \gamma = 170 \text{ Pb}^{82+} \). For this task, a comparatively simple setup was proposed, and tested during week 47 of 2010. The setup was mechanically and electronically tested and proved to be well-functioning, and a more elaborate setup is therefore planned for 2015 using the \( \text{Ar}^{18+} \) beam, but efficient usage requires the beam to be actively debunched.

5.1 Bremsstrahlung emission from \( \text{Ar}^{18+} \)

A relatively straightforward approach to derive the bremsstrahlung emission from a relativistic heavy ion, is to use the Bethe-Heitler cross section for bremsstrahlung emission from an energetic lepton and simply replace the electron mass by that of the ion, and likewise for the charge. This leads directly to a \( Z_1^2 \gamma \) dependence of the energy loss per unit path-length, as e.g. shown in [28]. However, in the rest-frame of the penetrating ion, the impinging virtual photons (in a Weizsäcker-Williams approach) that eventually lead to emission in the laboratory system of photons with energies of the order of that of the incident ion, will have a wavelength that is significantly smaller than the size of the nucleus. Such photons will therefore not interact with the nucleus as a whole, but instead ‘probe’ its interior, interacting individually with each of the charged constituents. This leads to a significantly reduced differential cross section \( d\sigma/d\hbar \omega \), and likewise a non-constant power-spectrum \( \hbar \omega d\sigma/d\hbar \omega \), as opposed to claims otherwise seen in the literature [28, 29].

Figure 5: Preliminary calculations of the cross section \( d\sigma/d\hbar \omega \) for bremsstrahlung emission from \( \text{Ar}^{18+} \) at 20 AGeV (left) and 150 AGeV (right), with the condition that the nucleus stays intact during the emission process. The dashed line shows the ‘traditional’ expectation including screening [30], whereas the dots shows the values based on the finite size of the impinging ion.

In figure 5 we show the expected spectrum compared to the ‘traditional’ expectation [28, 29, 30]. The location of the peak in the spectrum (dots) is given by \( 2\gamma \hbar \omega_1 \), where \( \hbar \omega_1 \) corresponds to the energy transfer above which the \( Z \) protons in the nucleus can be considered quasi-free. These preliminary calculations are based on the method by A.H. Sørensen [31, 25, 26], utilizing absorption cross sections for \( \text{Ar}^{18+} \) which - through use of the optical theorem - can be converted to elastic scattering cross sections. The tendency for the spectrum to fall off very steeply compared to other calculations, is an inherent feature of the treatment of the finite nuclear size.

5.2 Emission of delta-electrons

Generally, the energy of delta-electrons is limited by \( T_{\text{max}} \) given by

\[
T_{\text{max}} = \frac{2\gamma^2 \beta^2 m_e c^2}{1 + 2\gamma m_e / M + (m_e / M)^2} \approx 2\gamma^2 \beta^2 m_e c^2
\]  

(3)
where the last approximation - although typically described as the 'low-energy' approximation - in the present connection is sufficient for all practical purposes. However, the result eq. (3) is derived for a point-like projectile and the finite size of the nucleus leads to a quite different emission spectrum and an effective maximum energy that is significantly lower (although kinematically still given by eq. (3)).

Upon a change to the rest frame of the ion (practically the same as the center-of-mass frame) in which the electron is incident on the ion, the de Broglie wavelength $\lambda = h/p$ of the incident electron becomes comparable to the radius of the nucleus $R$, i.e. $\chi \equiv R/\lambda$ becomes larger than 1 [27]. Thus, the electron will ‘feel’ the constituents of the ion and therefore not register it as a point-like object of charge $Ze$ (in a sense similar to the virtual photons in the emission of bremsstrahlung).

![Figure 6](image-url)

Figure 6: Simulations for the generation of delta-electrons, using Ar$^{18+}$. The upper figure shows the expected distribution of delta-electrons for a homogeneously charged nucleus, the central figure for a point-like nucleus, and the lower figure for a nucleus with a Fermi distribution of charge. An average flux of Ar$^{18+}$ nuclei of 10,000 per minute, for 24 hours, is assumed.

In figure 6 is shown simulations based on the method shown in [27] for the generation of delta-electrons, using Ar$^{18+}$ projectiles [7]. In particular the left-hand side of the distribution, on the vertical symmetry axis, is sensitive to the exact model used. Further studies to determine the sensitivity to distinguish between the models is underway [7].
5.3 Requested beam and beam time

Due to the presence of the MUSIC detectors, which operate with a time-scale of a few microseconds, the proposed setup cannot accommodate more than about $10^5$ particles per burst. Moreover, the beam has to be actively debunched before extraction from the SPS (as it was done in previous runs before 2010), since projectiles arriving at the detectors with a separation time shorter than a few microseconds, means that the event has to be discarded.

In 2015, we request beam time with Ar$^{18+}$ with momenta per charge as for NA61: 13, 20, 30, 40, 80, 150 AGeV/c, and debunched. Intensities as low as $10^4$ ions per spill, for a day per momentum will be useful, which means that NA63 can probably run parasitically. For the future runs, we envisage doing measurements Pb$^{82+}$ (in 2016) and for Xe$^{54+}$ (in 2017).
6 Status of publications

Publications related to the activities of NA63:


References

[15] K.K. Andersen et al. (CERN NA63), CERN-SPSC-2009-038; SPSC-P-327-ADD-1, Addendum to Proposal