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A proposal to measure Coulomb background with a multilayer Beryllium target

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Abstract

For the choice of the Beryllium (Be) target ($Z = 4$) the value of the pionium breakup probability is low. This value is reduced even further if a multilayer target design is considered with vacuum gaps in the regions where most atoms in S ($l = 0$) bound states are annihilated. Such a target configuration yields essentially the same relative momentum spectrum as the Ni (98 μm) target, while being free from atomic pairs. A Tantalum scatterer placed after the Beryllium layers and the procedure of mixing two different data samples would lead to creation of the desired conditions.

1 Introduction

The experimental method for lifetime measurement of DIRAC needs a description of time correlated background pairs. The description of these pairs is made by using an accidental (non-time correlated) pairs sample. Although the procedure to obtain the time Coulomb correlated relative momenta spectrum from accidental pairs is theoretically well established [1], Coulomb correlation has never been measured with the necessary accuracy. Moreover, the Coulomb Correlation function to be applied to the accidentals needs a detailed knowledge of the resolution functions. Since the Coulomb correlation does not depend from the target, but only from phase space, we have studied the possibility of a target free from the contamination of atomic breakup pairs. Such a measurement would serve as a cross-check of the standard procedure that reconstructs the Coulomb background from accidentals.

Another uncertainty when parameterizing real pairs with accidentals is due to the different response of the SFD for real and accidental hits. The procedure therefore introduces systematic errors which can be only overcome by a dedicated measurement free from pairs from atomic breakups.

The design of a target system free from contribution of the atomic pairs should take into account several points:

Total thickness	Breakup Probability (without gaps)	Breakup Probability (with gaps)	$\epsilon(Be)/$ $\epsilon(Ni)$
375 μm	11.3%	6.3%	0.98
250 μm	9.8%	5.8%	1.48
150 μm	7.5%	5.0%	2.46

Table 1: Breakup probability for three different Beryllium target thicknesses. The third column shows the breakup probability for the target with 25 μm layers separated by 500μm gaps. The ratio between the nuclear efficiency of the Beryllium targets compared to the 98μm nickel target is shown in the forth column. The lifetime of pionium was assumed to be $\tau = 2.9 \cdot 10^{-15}s$.

Single Target Thickness	Number of Layers in the Target	Total Target Thickness	Breakup Probability (P_{br})
25 μm	10	250 μm	5.8%
25 μm	14	350 μm	6.2%
10 μm	25	250 μm	3.9%
10 μm	35	350 μm	4.4%
5 μm	25	250 μm	3.1%
5 μm	35	350 μm	3.2%

Table 2: Breakup probability for different Beryllium target setups. Different single layer and total target thicknesses have been studied. The layers are separated by 500μm gaps. The lifetime of pionium was assumed to be $\tau = 2.9 \cdot 10^{-15}s$.

- The breakup probability decreases with the target thickness.
- The breakup probability is smaller for target materials with low atomic number.
- The total yield of particles should be compatible with the one obtained with the standard data taking conditions in order to avoid undesired biases in the sample and/or detector response.
- Only a limited range of target thicknesses are available from the manufacturers.

Taking this into account we have searched an optimal design for the target setup.

2 Target design and breakup probability

We have studied several different configurations designed to decrease the breakup probability in the target. The main factor in this process is the choice of the target material. The interaction and the ionization cross sections increase with

Z, i. e., the lower Z the smaller the breakup probability. The best choice of the available target materials is Beryllium ($Z = 4$). For a Beryllium target of infinite thickness the pionium breakup probability is around 15% [2, 3]. It decreases with thickness and is zero for an infinitely thin target. However, the breakup probability increases very rapidly with the target thickness and hence, even for very thin targets we might have non-negligible breakup probability values.

On the other hand, in order for the nuclear efficiency of the Beryllium target to be compatible with the nuclear efficiency of the $98\mu m$ Nickel target, a total thickness of $370\mu m$ is required.

One way to achieve a low breakup probability along with the desired nuclear efficiency is by means of a multi-target array composed of thin layers [1]. This way one is able to find a balance between a small breakup probability (thin individual layers) and a large background pion pair yield (large overall thickness). Moreover, some amount of the created atoms would annihilate in the gap between two consecutive targets. However, the decrease of the breakup probability with the thickness of an individual layer is smaller than in the case of a single layer setup since a non-negligible amount of atoms in long-lived bound states (non S states) crosses the gaps and can break up in the next layer of the array [1]. We can observe this effect in the plot below (Figure 1).

We have performed breakup probability calculations for different single layer thicknesses of the multi-target [2]. In Table 2 we can see the results for several single layer and overall target thicknesses. After the discussions in the analysis meetings a $10 \times 25\mu m$ design was considered to be the best suited for the Beryllium multi-target setup since the value of the breakup probability was found to be small enough and the discrepancy for the nuclear efficiency with the Nickel target was not large. Also, the thicker individual layers would simplify the manufacturing process and increase the rigidity of the final multilayer target. Finally, the cost of manufacturing such a target configuration would be reduced.

In Table 1 we show the breakup probability for three different overall thickness of the target, both for the case with a five hundred micron gap between 25 μm layers and for a single layer target. The atoms in the target array were propagated making use of the interaction cross-sections calculated in [4]. These cross-sections are based on the Hartree-Fock description for the Beryllium atomic form factor which leads to slightly larger values for the breakup probability than the Moliere parameterization obtained in [2]. In [3] a comparison between the results obtained with these two sets of cross sections was made.

[1] This means that the breakup probability of a target array with layers of equal thickness will always be larger than what would be the breakup probability of a target made by of a single layer of this array.

[2] To perform these breakup probability calculations we have used and modified the Monte Carlo described in [5].

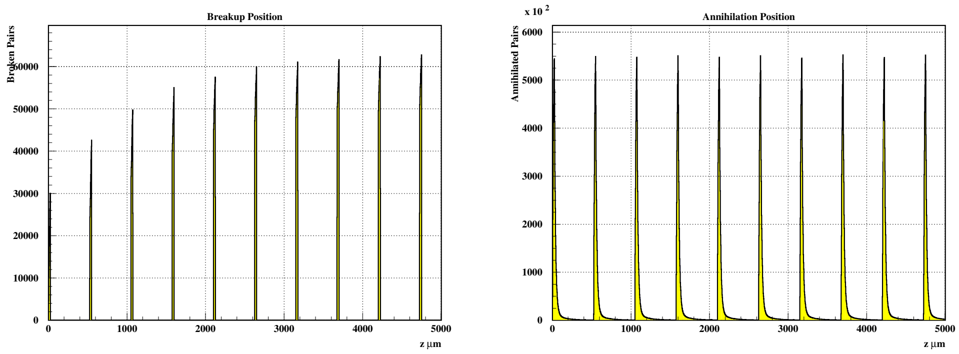

Figure 1: Breakup (left) and Annihilation (right) position for the atoms in a $10 \times 25\mu m$ Beryllium multi-target setup.

3 Additional scatterer to reproduce Δx distribution

It is an established fact that the multiple scattering in a target has a large contribution to the low value region of the relative momentum distribution of pion pairs. However, since the radiation length in Beryllium is much smaller than in Nickel [3] the multiple scattering for the proposed Beryllium target would be much smaller and hence the relative momentum distribution for both atomic and Coulomb pairs would be different from the one in a Nickel target.

But this is precisely what we would like to avoid since we want the Beryllium target to provide us with a spectrum, from which Coulomb background distribution free from atomic pair contribution for the Nickel target could be obtained. Thus it was proposed to add an additional layer of Tantalum scatterer a few centimeters away from the primary target. In principle, this scatterer should be placed as close to the primary target as possible to avoid bias in the reconstructed momenta. However, there are two possible difficulties with this configuration. The first one is the fact that the interaction of the proton beam halo with the scatterer could contaminate our sample with a undesirably large background. The second one is the lack of available space in the vacuum chamber after the target setup. After studying the problem the minimum distance from the target to the scatterer was set to 35 cm [10].

We have also performed a simulation [4] in order to optimize the thickness of

[3] To produce the same multiple scattering effect as the $98\mu m$ Nickel target a $2000\mu m$ thick Beryllium target is required.

[4] The atomic pairs generation has used the Monte Carlo for breakup probability calculation together with the $1S$ and $2S$ bound states spectra [7]. When an atom was broken from a different state the $1S$ state spectrum was used scaling the resulting Q by $1/2n$ [8], where n is the principal quantum number of the bound state.

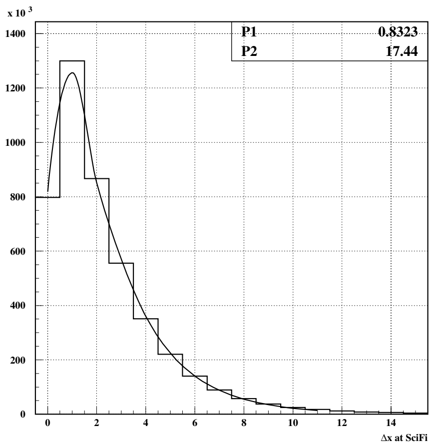

Figure 2: Parameterization of the difference in the hit fiber for an atomic data sample. The parameter $P1$ accounts for the Tantalum scatterer thickness in μm, meanwhile $P2$ accounts for the percentage of the sample "with" the scatterer (83.%).

the scatterer by trying to reproduce the Nickel Δx distribution of atomic pairs for the x-plane of the scintillating fiber detector for the Beryllium target [5]. We have chosen the Δx criteria, since we would like to reproduce the Q spectrum after reconstruction and the differences between the proposed target-scatterer system and the original target of DIRAC due to differences in multiple scattering, which affects mostly the transverse component of relative momentum. Moreover, Q_T is proportional to the Δx distance at the level of the x-plane of the scintillating fiber detector. If we are able to reproduce the same Δx distribution for both samples we would also be able to reproduce the same Q_T spectrum.

As a second parameter we have considered a combination of samples "with" and "without" the scatterer. The Δx distribution for atomic pairs has been parameterized as a function of the scatterer thickness and the data samples "with" and "without" the scatterer.

As an example in Figure 2 we show the result of this optimization for a Beryllium $10 \times 25\mu m$ target. We see that, if we add 83% of the events with a $17.87\mu m$ Tantalum scatterer and 17% without a scatterer, the Beryllium target setup reproduces fairly closely the Δx distribution for the Nickel target.

[5] Even though the Beryllium target breakup probability is very low, we have chosen an atomic pair sample since they concentrate in the region of interest $Q < 2MeV/c$. For $Q > 2MeV$ the Nickel target is also almost free from atomic pairs.

Under these conditions we have generated atomic and Coulomb pairs [6] [7] "with" and without a $17.87\mu m$ scatterer. Subsequently we have mixed these two samples according to the resultant relative proportions (83% for the one "with" scatterer and 17% for the one "without" it) and made the cut $|Q_x| < 4MeV/c$ and $|Q_y| < 4MeV/c$, which is used in the experimental data analysis. The comparison of either of the two samples, "with" and "without" scatterer, and the combined sample with the original Nickel $98\mu m$ sample at the generation level is shown in Figure 3 for Δx distributions at the SciFi detector level and in Figures 4 and 5 for the Q relative momentum and its Q_L and Q_T components. However, we should not expect a complete agreement of the Q distributions before reconstruction, especially those of the Q_T, since the optimization was made for Δx, the distance between the two particles, and the events "with" the scatterer increase their relative momentum at 35 cm from the target and hence need a larger Q_T to reproduce the same Δx distance at the SciFi. This explains the discrepancies between the two sets of distributions of Figure 5.

4 Reconstructed events

As a test of the study we have processed three different samples of events (1.2×10^6 Nickel events, 1.2×10^6 Beryllium events "with" scatterer and 0.32×10^6 Beryllium events "without" scatterer) with Dirac-Geant [11] Monte Carlo and then reconstructed them with the ariane304_18 [12, 13] [8]. The goal of this study was to check whether the combined distributions of Beryllium reproduce the Nickel ones. The results are shown in Figures 6 and 7, where we can see a reasonable agreement for the combination of the two different samples.

In Figure 8 we plot the results taking into account the the combination of atomic and Coulomb pairs. If we add the atomic distributions to the Coulomb ones and subtract the resulting spectra for Nickel and Beryllium we should obtain atomic Nickel distribution. We can see in the third plot of Figure 8 that the disagreement is not very large for the $Q < 2MeV/c$ region but is not completely satisfactory for the higher Q's.

To improve this result we have followed a slightly different strategy. For the Nickel sample we made a fit of the Coulomb spectrum as a function of the Beryllium distribution "with" and "without" scatterer in the region free from atomic pairs ($4MeV/c < Q < 15MeV/c$).

[6] We have not considered "non-Coulomb" pairs in this study. However the main contribution in the low Q region should be given by "Coulomb" pairs.

[7] The relative momenta of Coulomb pairs were generated according to the Sakharov formula [9]:

$$\frac{d\sigma_s}{dQd\theta} \propto \frac{2\pi M_\pi \alpha/Q}{1-e^{-2\pi M_\pi \alpha/Q}} Q^2 \sin\theta,$$

where θ is the angle between the direction of the center of mass momentum and the relative momentum. We have imposed a $|Q_x| < 10MeV/c$, $|Q_y| < 10MeV/c$ and $Q < 30MeV/c$ cut to the generated events.

[8] The cuts $|Q_x| < 4MeV/c$ and $|Q_y| < 4MeV/c$ were performed after reconstruction.

$$\frac{dN^C_{Ni}(Q)}{dQ} = A \times \frac{dN^C_{Be}(Q)}{dQ} + B \times \frac{dN^C_{Be+Ta}(Q)}{dQ}$$

where A and B are free parameters to be obtained from the fit. The result of the fit gives $A = 0.234$ and $B = 0.735$. If we combine the Beryllium spectra "with" and "without" scatterer taking into account these two coefficients, we obtain the result of Figure 9. We can observe from this figure that the agreement after subtraction is much closer and general within statistical error.

Notice that in both cases, either when we used the original percentages calculated to optimize the Δx distributions or with the fit of the reconstructed spectra of Coulomb pairs, the coefficient of the sample "without" scatterer is significantly smaller than the "with" scatterer one. This means that the use of the scatterer is mandatory if we want to precisely reproduce the Ni results with the Be multi-target setup.

5 Conclusions

We have shown that it is possible to reproduce the relative momentum spectrum of Coulomb pairs for standard Nickel target with a $10 \times 25\mu m$ Beryllium multi-target array combined with a 17.87 μm Tantalum scatterer placed 35 cm away from the primary target. The Beryllium target design has been proposed according to low breakup pairs contamination criteria but manufacturing and economical constraints have also been considered. The scatterer thickness has been optimized to reproduce the Δx distribution in the Scintillating Fiber detector and found to be $17.87\mu m$ for the proposed Beryllium target. The study of the relative momentum distributions after reconstruction has been made and it has been shown that the atomic distribution can be measured with the parameterization of the background with two Beryllium samples "with" and "without" scatterer by using an appropriate fit.

Acknowledgements

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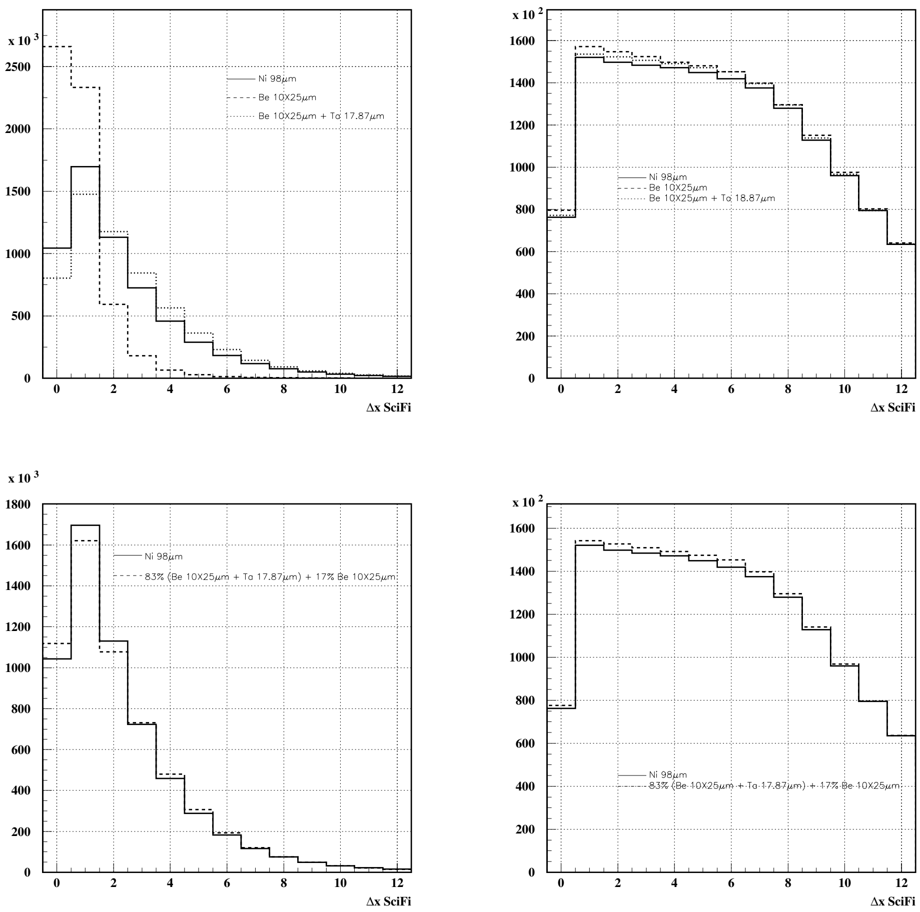

Figure 3: Upper, Δx distribution comparison between the original Ni $98\mu m$ simulated data and the $10 \times 25\mu m$ Be target "with" and "without" scatterer. Lower, the comparison between the Ni target and the combined distribution of Be 83% "with" and 17% "without" scatterer. Left side, atomic pairs. Right side, Coulomb pairs.

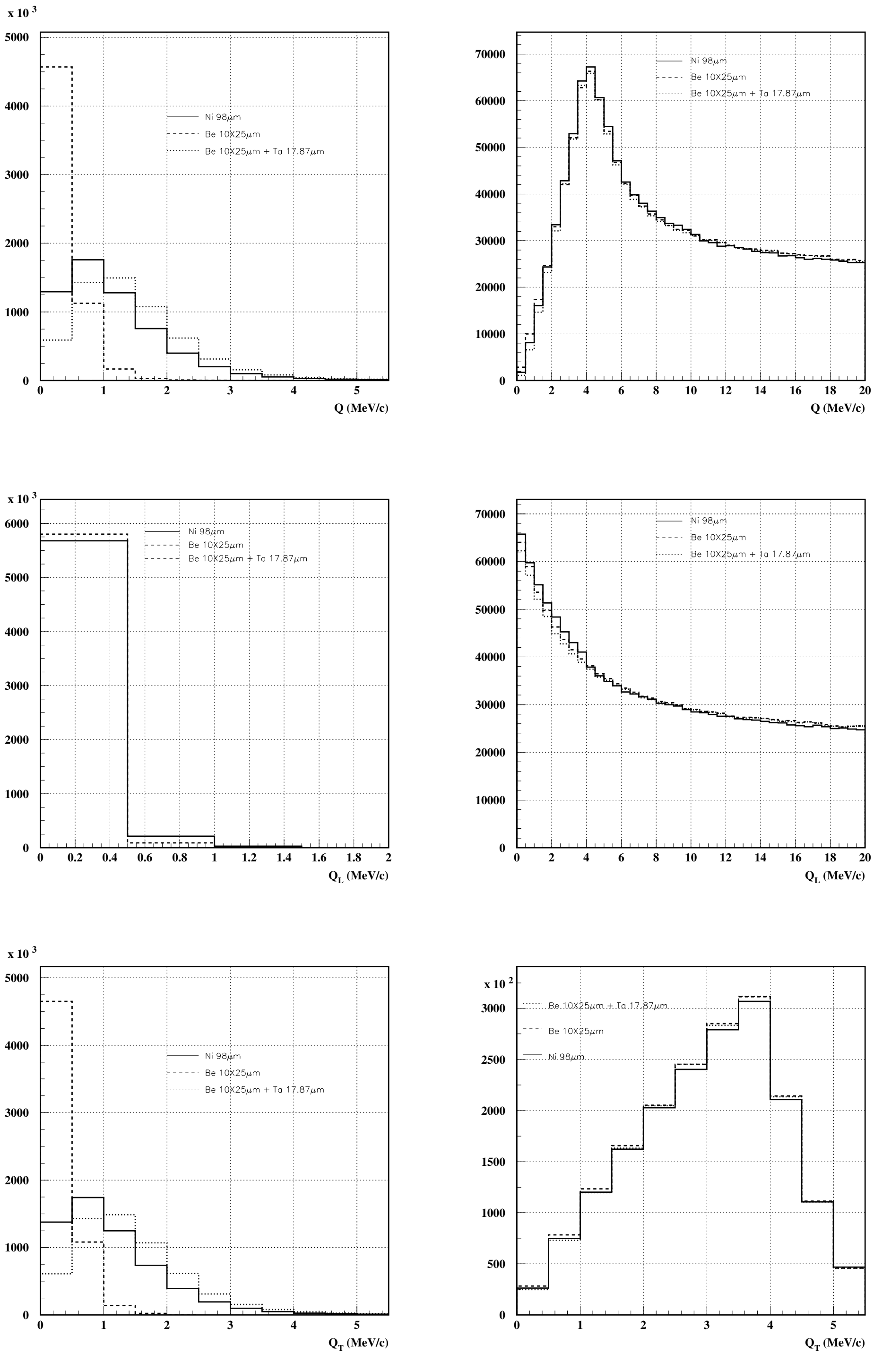

Figure 4: Relative momenta. Comparison between the original Ni $98\mu m$ simulated data and the $10 \times 25\mu m$ Be target "with" and "without" scatterer. Left side, atomic pairs. Right side, Coulomb pairs.

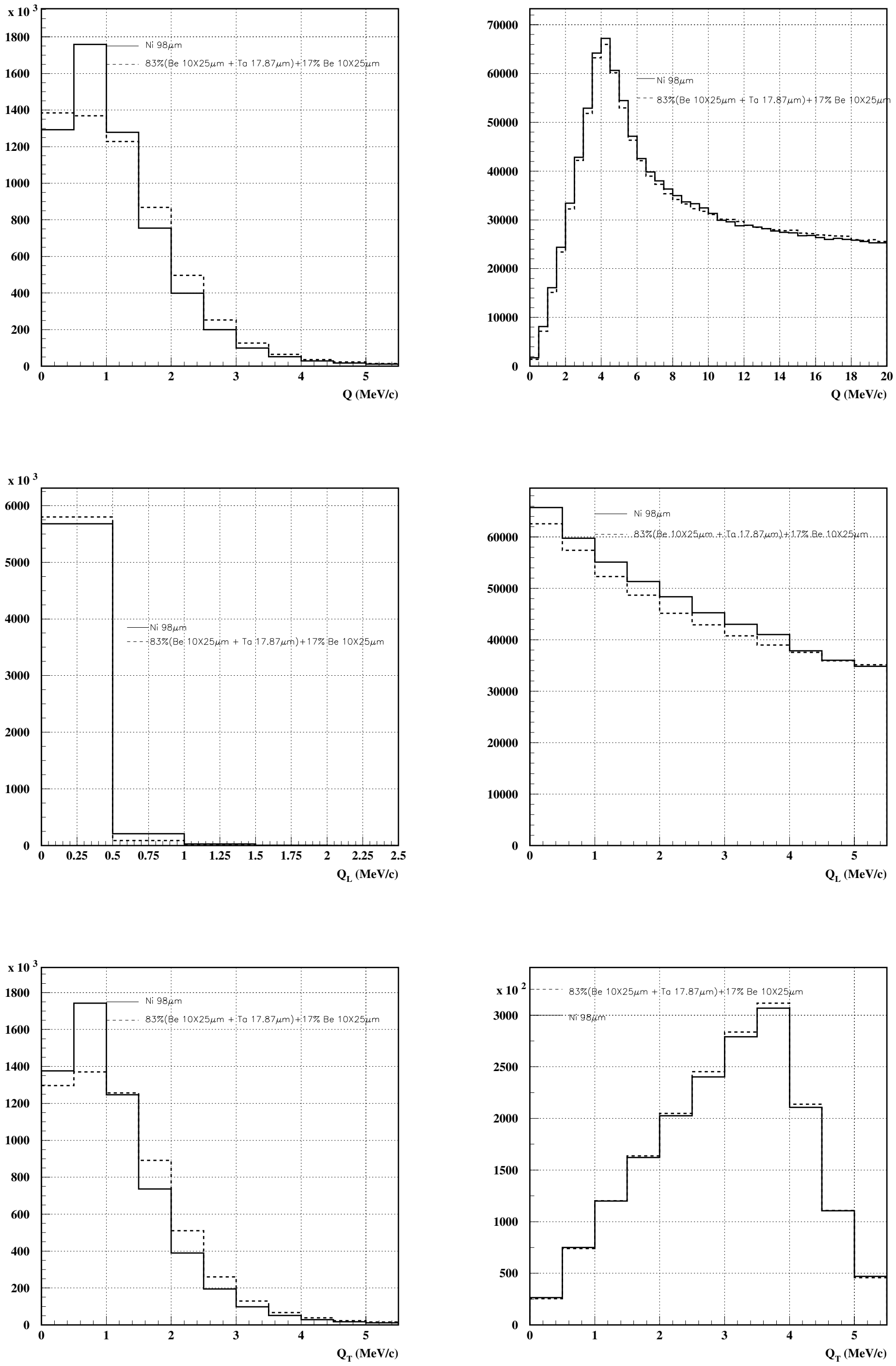

Figure 5: Relative momenta. Comparison between the original Ni $98\mu m$ simulated data and the combined sample of 83% $10 \times 25\mu m$ Be target "with" scatterer and 17% $10 \times 25\mu m$ Be target "without" scatterer. Left side, atomic pairs. Right side Coulomb pairs.

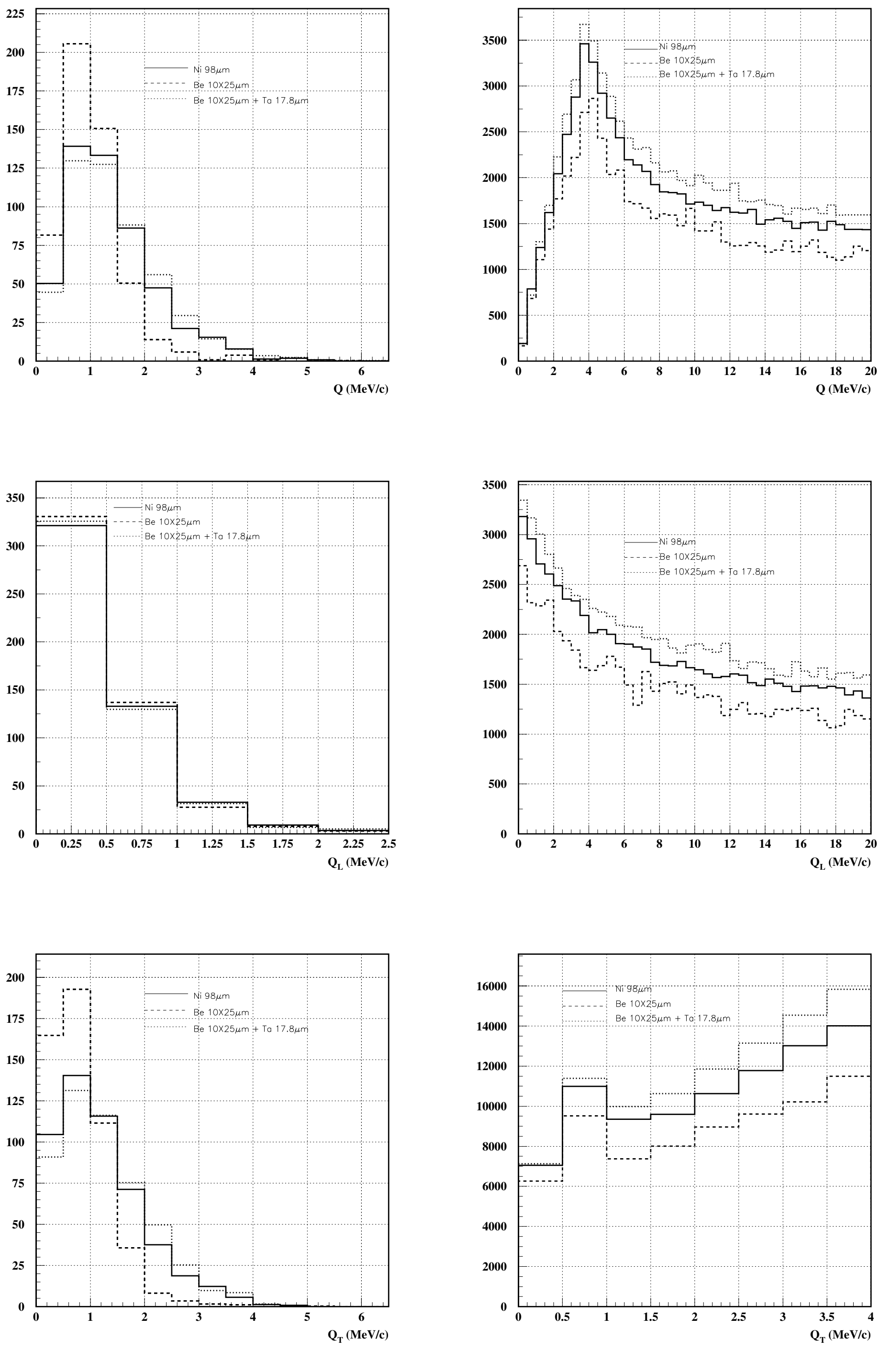

Figure 6: After Reconstruction. Relative momenta comparison between the original Ni $98\mu m$ simulated data and the $10 \times 25\mu m$ Be target "with" and "without" scatterer. Left side, atomic pairs. Right side, Coulomb pairs.

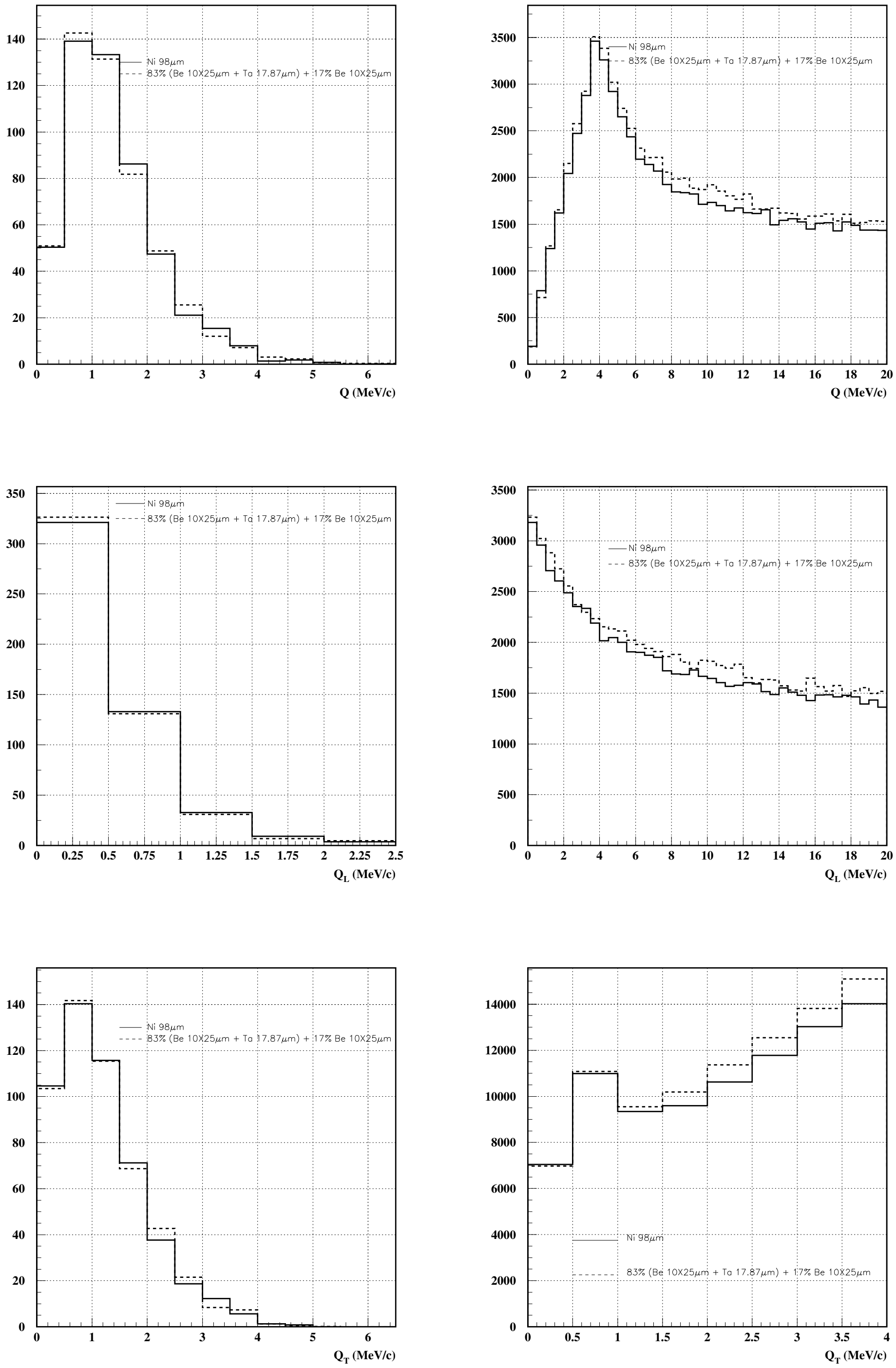

Figure 7: After Reconstruction. Relative momenta comparison between the original Ni $98\mu m$ simulated data and the combined sample of 83% $10 \times 25\mu m$ Be target "with" scatterer and 17% $10 \times 25\mu m$ Be target "without" scatterer. Left side, atomic pairs. Right side Coulomb pairs.

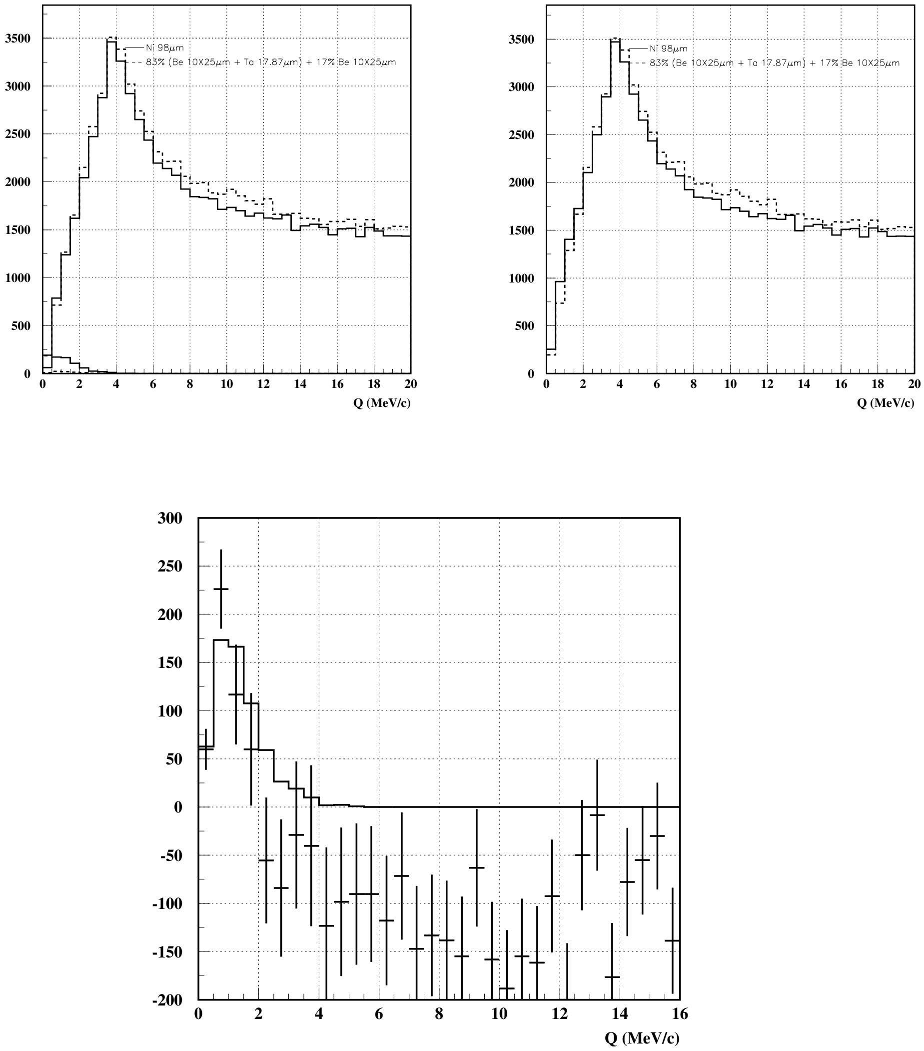

Figure 8: After Reconstruction. Upper Left: Relative momenta comparison between the original Ni $98\mu m$ simulated data and the combined sample of $10 \times 25\mu m$ Be target. Atomic and Coulomb pairs are shown separately. Upper Right: Relative momenta comparison between the original Ni $98\mu m$ simulated data and the combined sample of 83% "with" and 17% "without" scatterer $10 \times 25\mu m$ Be target. Atomic and Coulomb pairs are combined. Lower: The subtraction of the upper right Nickel minus Beryllium distribution (crosses) should give us the original distribution of atomic Nickel pairs (solid line).

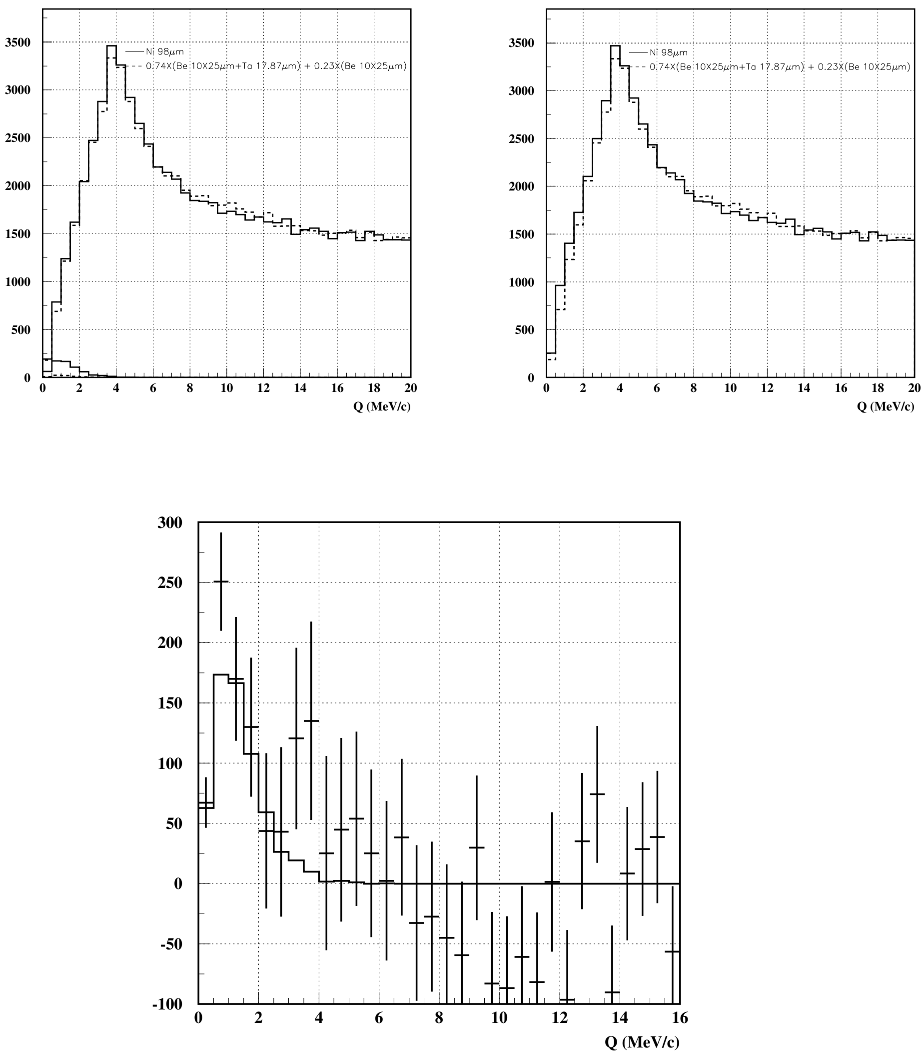

Figure 9: After Reconstruction. Upper Left: Relative momenta comparison between the original Ni $98\mu m$ simulated data and the combined sample of of 0.74 "with" and 0.23 "without" scatterer $10 \times 25\mu m$ Be target. Atomic and Coulomb pairs are shown separately. Upper Right: Relative momenta comparison between the original Ni $98\mu m$ simulated data and the combined sample of of 0.74 "with" and 0.23 "without" scatterer $10 \times 25\mu m$ Be target. Atomic and Coulomb pairs are combined. Lower: The subtraction of the upper right Nickel minus Beryllium distribution (crosses) should give us the original distribution of atomic Nickel pairs (solid line).