Final report for the OTKA/NKFIH project entitled "Precision study of exotic nuclear decays"

No: K 124810

The most important results of the project are summarized briefly below with references to our publications

Inspired by new theoretical predictions connected to our recent results [1, 2] we will report on 6 main results, that we have achieved with the help of this grant. These include:

1. We upgraded the electron-positron spectrometer with modern Double Sided Silicon strip Detectors (DSSD), connected to novel electronics and data acquisition system [12].
2. We repeated the experiments for ^{8}Be [4, 5, 6, 7, 9, 10] and obtained consistent results with our first results [1].
3. We have found signatures of the X17 particle creation and decay in ^{4}He using the ^{3}H(p,γ)^{4}He nuclear reaction [9, 10, 12].
4. We have studied also the double γ-decay in ^{4}He using the ^{3}He(n,γ)^{4}He and ^{3}H(p,γ)^{4}He nuclear reactions but found no signature of the X17 γ-decay [8].
5. We have found signatures of the X17 particle creation and decay in ^{12}C using the ^{11}B(p,γ)^{12}C nuclear reaction [14, 15].
6. We have constructed a new, even more precise, electron-positron spectrometer with two layers of high resolution DSSD detectors for each telescope to track the electrons and positrons. It will be used for systematic studies of the creation and decay of the X17 boson in different other nuclei. A technical report about this spectrometer will be published soon, and is discussed in a bit more detail in this report. Necessiating the inscreased length (9 pages) of the report.

1 Upgrading the electron-positron pair spectrometer

As the main improvement of our previous experimental setup [1, 11], the MultiWire Proportional Chambers (MWPC) have been replaced by novel Double-sided Silicon Strip Detectors (DSSD). They were placed very close to the front face of the scintillators to enhance the efficiency of the experimental setup and its homogeneity [12].

We also increased the number of telescopes from five to six. The positions of the hits were registered by the DSSDs having sizes of 50×50 mm^2, strip widths of 3 mm and a thickness of 500 μm.

The signals from the DSSD detectors were processed with a 16 channel preamplifier, shaper and discriminator units with multiplexed readout (MUX-16). Time and energy signals of the scintillators, as well as the time, energy and position signals of the DSSD detectors were recorded. The details of the upgraded spectrometer and their calibration procedures are described in Ref. [12].

2 Repeating the ^{8}Be experiments with the upgraded electron-positron pair spectrometer in the new Tandetron Laboratory

We re-investigated the ^{8}Be anomaly with the improved experimental setup. We have confirmed the signal of the assumed X17 particle and measured its mass and branching ratio with improved precision [3, 4, 5, 6]. The observed deviation in the angular correlation of the e^+e^- pairs was found much smaller for the 17.6 MeV than in the 18.15 MeV transition of ^{8}Be [3].

3 Searching for signatures of the X17 particle creation and decay in ^{4}He using the ^{3}H(p,γ)^{4}He nuclear reaction

As a next project, we have conducted a search for the X17 particle in the ^{3}H(p,e^+e^-)^{4}He reaction, which has a much larger Q value of 19.813 MeV. We could reach much higher excitation energies in ^{4}He than previously in ^{8}Be where the Q value was 17.254 MeV.

The experiment was performed in Debrecen at the 2 MV Tandetron accelerator of ATOMKI. The ^{3}H(p,e^+e^-)^{4}He reaction was used at proton bombarding energies of E_p = 510, 610 and 900 keV.

The main features of the angular correlatios can be understood by taking into account the internal and external pair creations following the proton capture by ^{3}H. However, these processes cannot account for an observed peak around 115° in the angular correlation spectra. This anomalous excess of e^+e^- pairs can be described by the creation and subsequent decay of a light particle during the direct capture process.

The derived mass of the particle is $m_{\mathrm{X}}c^2 = 16.94 \pm 0.12$(stat.)$\pm$0.21(syst.) MeV [12]. According to the mass this is likely the same X17 particle, which we recently suggested [1] for describing the anomaly observed in the decay of ^{8}Be.

The direct capture has a dominant multipolarity of E1. This supports the vector character of the X17 particle.

4 Searching for the double γ-decay of the X(17) particle

We studied the $\gamma\gamma$-decay of the 17 MeV particle candidate in order to distinguish between the vector or the pseudoscalar boson scenario, both of which have been suggested recently by different theoretical groups interpreting our previous experimental observations.

We have performed two experiments to find out which is the right scenario. According to the Landau-Yang theorem, the $\gamma\gamma$-decay of a massive, $J = 1^+$ or $J = 1^-$ particle is strictly forbidden. Therefore, we searched for possible signatures of the X(17) $\gamma\gamma$-decay in the ^{3}H(p,e^+e^-)^{4}He and in the ^{3}He(n,e^+e^-)^{4}He reactions, in ATOMKI and in the Garching high-flux reactor FRM II of the Technical University Munich. However, no clear indication of a boson decay was observed [8]. This result also supports the vector character of X17.

5 Searching for signatures of the X17 particle creation and decay in ^{12}C using the ^{11}B(p,γ)^{12}C nuclear reaction

Our very latest results were obtained by the examination of the ^{11}B(p,γ)^{12}C nuclear reaction. The reaction was studied between E_p= 1.5 MeV and 2.5 MeV at five different bombarding energies. After taking into account the average proton energy loss in the target (ΔE=0.2 MeV) the excitation energy range was 17.0$\leq E_x \leq$18.0 MeV, covering the high energy part of a broad resonance (E_x=17.2 MeV, $J^\pi = 1^-$, Γ = 1.15 MeV).

This reaction has a large cross section, so the resulting γ-rays are also widely used to calibrate detectors. The resonant energy for protons according to the literature is E_p = 1.388 MeV.

Because the width of the state is large (Γ = 1.15 MeV), a 2 mg/cm^2 thick ^{11}B target was used to achieve adequate yields for e^+e^- pairs. The target was evaporated onto a 5 μm thick Ta foil. The Plexiglas rods that we used previously for holding the targets [1, 11], were replaced with Al rods to get a better cooling of the target. In this way we managed to significantly increase the lifetime of the target.

The energy of the bombarding protons was chosen to be E_p = 1.5, 1.7, 1.88, 2.1 and 2.5 MeV. The proton beam impinged on a ^{11}B target with a typical current of 2.0 μA for about 50 hours at each beam energy. In the end, the first target survived the whole experiment.

5.1 Experimental results

In order to search for the assumed X17 particle, both the sum-energy spectrum of the e^+e^- pairs measured by the telescopes, and their angular correlations, determined by the DSSD detectors, have been analyzed. Since the counting rates in the detectors were low ($\approx$ 150 Hz in the scintillators and $\approx$ 25 Hz in the DSSD detectors) and the coincidence time window was sharp ($\approx$ 10ns) the effect of random coincidences was negligible. In the followings we show only the real coincidence gated spectra.

In GEANT simulations both e^+e^- pairs generated by internal pair creation in the target and the e^+e^-- pairs generated by external pair creation in the Ta backing were taken into account. A more detailed description of the simulations can be found in Ref. [12].

The experimental determination of the efficiency of the e^+e^- spectrometer was carried out using consecutive uncorrelated e^+e^--pairs as previously described [1, 3, 4, 10].

In order to derive the value for the mass of the decaying particle from the present data, we carried out a fitting procedure for both the mass value and the amplitude of the observed peak. The fit was performed with RooFit as described previously [12].

A significant background is obtained from the E1 transition at large angles, but the contribution from the assumed particle decay is also significant in the same region. The significance of the peak observed is measured to be higher than 6σ in all cases.

The measured masses of the particle and its branching ratios, as derived from the fits, as well as their averages, are summarized in Table 1. We obtained compatible values for each fitted parameter.

Table 1 displays only the statistical errors. The systematic uncertainties were estimated from the simulations in a similar way as in previous works [12], and resulted in: $\Delta m_{\rm X}c^2$(syst.) = $\pm$0.2 MeV. It is mostly coming from the uncertainty of the beam spot position on the target, which turned out to shift by about $\pm$2 mm during the experiment.

Table 1: X17 Boson branching ratios (B_x), masses, and confidences derived from the fits.

E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	2.7(2)	16.62(10)	8σ
1.70	3.3(3)	16.75(10)	10σ
1.88	4.1(4)	16.94(10)	11σ
2.10	4.7(9)	17.12(10)	6σ
Averages	3.4(3)	16.86(17)	
Previous [1]	5.8	16.70(30)	
Previous [12]	5.1	16.94(12)	
Predicted [13]	3.0		

The obtained mass agrees very well with that observed in the earlier ^{8}Be and ^{4}He experiments, which is remarkable, and gives strong kinematical evidence for the existence of the X17 particle.

The obtained branching ratio for the X17 decay differs from the previous data, but agrees well with the theoretically predicted value [13], which is also shown in the last row of the table.

In summary, we have studied the E1 ground state decay of the 17.2 MeV $J^\pi = 1^-$ state in ^{12}C. The energy-sum and angular correlation spectra of e^+e^- pairs produced in the $^{11}B(p,e^+e^-)^{12}C$ reaction at E_p= 1.50, 1.70, 1.88, 2.10 and 2.50 MeV proton energies were measured. The main features of the spectra can be understood rather well by taking into account the internal and external pair creations following the the decay of the 1^- resonance.

However, on top of that smooth distributions we observed significant peak-like anomalous excess of e^+e^- pairs in the angular correlation spectra around 155° at 4 beam energies.

This e^+e^- excess can be described by the creation and subsequent decay of the X17 particle, which we recently suggested [1, 12]. The derived mass of the particle ($m_X c^2 = 16.86 \pm 0.17$(stat.)± 0.20(syst.) MeV) agrees well with our previous measurements. The observed branching ratio is: $3.4(3) \times 10^{-6}$. Observation of the X17 particle in the above E1 transition supports its vector character, as suggested also by Feng et al. [13].

With the X17 particle appearing to be created in the E1 transition, we are forming plans to search for it in the decay of Giant Dipole Resonance (GDR) excitations of different nuclei as well.

Our latest results on ^{12}C have been published only in ArXiv [14], but it was submitted for publication in Phys. Rev. and at the same time I presented invited talks about it in the following workshops and conferences:

1. Invited talk at the workshop on “Shedding light on X17” in Rome, in September 6-8, 2021 (https://agenda.infn.it/event/26303/).

2. Keynote speaker at the syposium on Frontiers of Fundamental Physics (FFP15) 23rd - 26th May 2022 (https://ffp15.istanbul.edu.tr/en/).

3. Plenary talk at the traditional meeting of Hungarian Physicists and Physics Teachers, organized by the Loránd Eötvös Physical Society with a title of “A new particle is being born in ATOMKI” in August 21-24, 2022 (http://elft.hu/magyar-fizikus-vandorgyules-2022/).

6 Constructing a new pair spectrometer for measuring electron-positron angular correlations from energetic nuclear transitions

A new electron-positron pair spectrometer has been designed and constructed for the simultaneous measurement of the energy- and angular correlation of e^+e^- pairs.

Spectroscopy of internal pair conversion (IPC) has a long tradition. In a wide range of energies and atomic numbers, the conversion coefficients for internal electron-positron pair formation are fairly high, typically in the order of 10^{-4}-10^{-3}. The measurement of these coefficients offers an effective method for determining the multipolarity of electromagnetic transitions (especially of high-energy and low-multipolarity transitions). The spectrometer is also designed to search for deviations from IPC due to the creation and subsequent decay into electron-positron pairs of a hypothetical X17 short-lived neutral boson.

An overview of pair spectrometers and a detailed description of an electron-positron spectrometer we used before [1] can be found in Ref. [11].

The main idea of the improvement was, to use DSSD detectors with two times better space resolution in both x and y directions than the ones we described in sections 1-5, and use two layers of detectors to be able to track the electrons and positrons.

6.1 Monte Carlo Simulations

Simulations for the new spectrometer were performed by GEANT3, and later on by GEANT4, taking the full experimental setup into account. This included the target, its backing, the target holder and all materials in the vicinity of the target and the detectors; the packaging of the detectors, the light guides and the various pieces used to mount the detectors.

The computer simulation of particles traversing the experimental setup takes into account the interactions of those particles with the material of the detector. GEANT is able to simulate the dominant processes which can occur in the energy range from 10 keV to 10 TeV for electromagnetic interactions.

The length of the detector telescopes was large enough (80 mm) to stop almost all 20 MeV electrons or positrons. The γ radiations created by bremsstrahlung or annihilation could in some cases escape from the detectors, resulting in distorted peak shapes.

The simulation follows the tracks of the primary electrons and positrons through the setup, together with secondary particles induced by γ-s, including the annihilation γ-s. The detected energy losses in the scintillators are kept track of, including the kinetic energy that is left over at the end of a track when the particle stopped inside the scintillator.

e^+e^--pairs from E/M IPC transitions were generated for the detector simulation according to the Rose calculations. e^+e^--pairs from a hypothetical intermediate boson decay could also be generated, as well as background processes like $\gamma-\gamma$ coincidences, single high energy gamma events, and traversing cosmic muons.

6.2 Construction of the spectrometer

The spectrometer is designed to be properly modular to make any repairs easier. The spectrometer consists of 6 identical modules (telescopes). Such a module includes easy-to-extract EJ200 plastic scintillators and optically attached Hamamatsu 10233-100 photoelectron multipliers, as well as a DSSD module. A CAD drawing of such a telescope module is shown in Fig. 1.

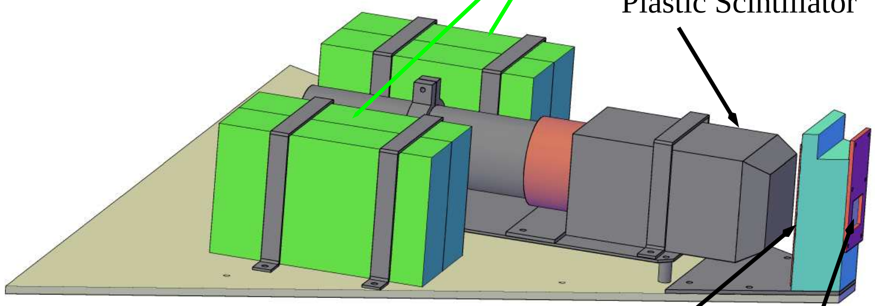

Figure 1: CAD figure of one telescope of the e^+e^- spectrometer

The detectors operate in air, as the energy loss of electrons in air is only ≈3 keV/cm. Electrons generated in the target are released to the air by passing through a thin wall (1 mm) carbon fiber target chamber. Their energy loss during their passage is less than 400 keV, and their angular scattering is less than 5°. The whole spectrometer is shown in Fig. 2.

The DSSD module consists of a detector holder made of POM (Polyoxymethylene) material but lined with an Al foil, and 2 DSSD detectors. The front detector, which is closer to the target is 300 μm thick so that the small-angle scattering of electrons in it is less than 5° degree. The outer surface of the detector is protected from external electrical noise by a 10 μm thick Al foil glued to a PCB board.

The size of the detector is 25x25 mm^2, and to determine the place of passage of electrons, 1 mm wide strips are used. On one side the x coordinates are determined, and on the other the y ones, using stripes perpendicular to each other.

On the other side of the detector holder is a larger DSSD detector with a surface area of 50x50 mm^2 and a thickness of 500 μm. The width of the x,y strips in this case was 1.5 mm. The side of this detector facing the scintillation detector is also protected from external noise with an Al foil. Special care was taken to properly ground the Al foils shielding the detectors.

Before building the spectrommeter we have performed detailed Monte Carlo simulations as described before.

The biggest challenge in building the spectrometer was minimizing the noise level of the electronics associated with the DSSD detectors. In the case of a 300 μm thick detector, the average energy loss of electrons/positrons is only 100 keV based on our simulations. Therefore, taking into account the energy distribution of electrons, we had to reduce the discriminator level to less than 60 keV in order to detect at least 90% of the electrons.

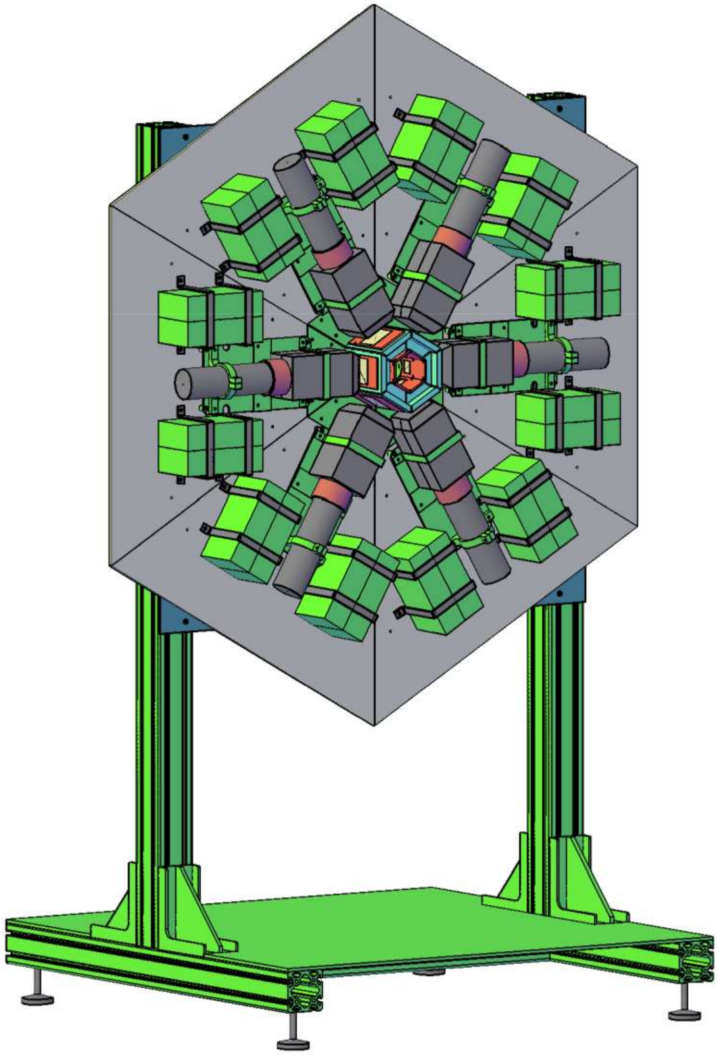

Figure 2: CAD figure of the e^+e^- spectrometer

The distance between the outputs of the detectors and the inputs of the multiplexers processing their signals is about 25 cm. The capacity between the wires of such a long shilded ribbon cable and their shielding is about 50-60 pF. Thus, this task could not be solved with a conventional ribbon cable. We had to make a special, low-capacity (12-15 pf) ribbon cable for it. With the help of such cable we managed to reduce the noise level of the detectors to less than 50 keV. In addition, in order to avoid ground loops, we had to be very careful about proper grounding and proper shielding of the entire detector system.

To digitize the electronic signals from the detector, we used 32-channel ADC, TDC and QDC units operating in a VME frame. The data was read out using a VME frame controller, which was connected to a USB port of a PC. The data acquisition software we wrote also made it possible to save events in files on disc and monitor them online. A photo of the entire spectrometer and the associated data acquisition system in shown in Fig. 3., which shows the shielding plates as well for 3 telescopes.

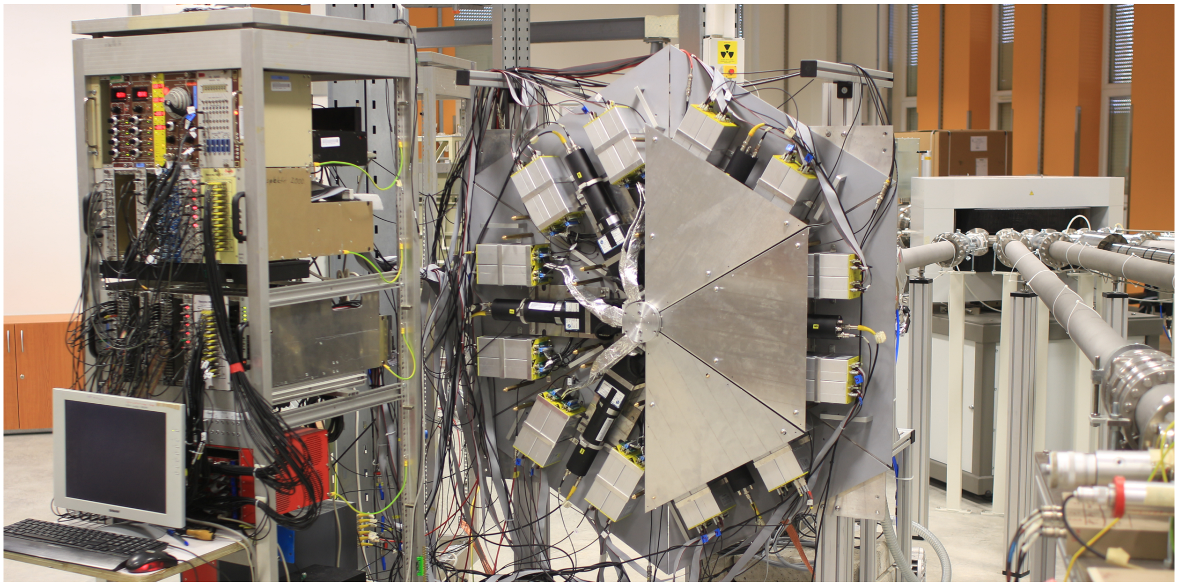

Figure 3: Photo of the new e^+e^- spectrometer in the Tandetron Laboratory

6.3 Trigger for data readout and data-acquisition

The signals from the photomultipliers of the E detectors are processed in constant fraction discriminator units (CF8000). The CFD thresholds are adjusted slightly above the noise level. The CFD unit supplies a mutiplicity signal, whose amplitude is proportional to the number of detector hits. This signal is then fed into a fast discriminator unit requiring multiplicity-2 coincidences. In order to allow the simultaneous measurement of single telescope events, a trigger box was set to allow a scaled-down fraction of single telescope events as well.

The signals from the DSSD detectors are processed with a 16 channel preamplifier, shaper and discriminator units with multiplexed readout (MUX-16). Up to two simultaneously responding channels can be identified and the two aplitudes plus the two corresponding amplitude coded addresses are sent to the bus. These units are especially well suited for DSSD single or double hit applications. The unit also provides ORed signals of the timing discrimitors.

Time and energy signals of the scintillators, as well as the time, energy and position signals of the DSSD detectors can be recorded.

To test and calibrate the spectrometer, the e^+e^- pairs generated from the ^{7}Li(p,γ)^{8}Be reaction at the resonance of E_p= 441 keV were used. The tracks of electrons originating from the target and passing through both DSSD detectors can be determined by the x,y coordinates measured with the 2 DSSD detectors. The data are currently being analysed.

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