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# Feasibility of photoelectron sources with sharp lines of stable energy between 20 and 80 keV

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ABSTRACT

Photo-absorption of $\gamma$−rays in thin Al, Co, Ti, and Mo convertors was examined with the aim to produce quasi monoenergetic photoelectrons having an energy spread of 0.5–4.7 eV about mean kinetic energies at discrete values between 18632 and 80321 eV. The photoelectron rates were estimated for commercial photon sources of $^{241}$Am, $^{119m}$Sn, $^{125m}$Te and $^{109}$Cd with activities of 0.55–3.7 GBq. Photoelectrons ejected by $^{241}$Am $\gamma$- and X-rays from Co convertors were measured with two different electron spectrometers and obtained energy spectra were compared with Monte Carlo predictions.



## 1. Introduction

The energy calibration of photon spectrometers is often performed with the $\gamma$−and X-rays emitted by commercial radionuclide standards. The calibration of electron spectrometers is usually done using internal-conversion or Auger electrons. This is more difficult since the energy of these electrons depends on the chemical state and environment of radioactive atoms which can change with time. On the other hand, metallic convertors (with their surfaces cleaned by ion sputtering) irradiated by $\gamma$−rays might supply photoelectrons with a more stable kinetic energy than have the conversion or Auger electrons emitted from open radioactive sources.

The present work was motivated by the need of the Karlsruhe Tritium Neutrino experiment (KATRIN Collaboration, 2001) that builds a large electrostatic retardation $\beta$−ray spectrometer with magnetic adiabatic collimation (the MAC-E-filter). This instrument should allow the investigation of the uppermost part of the tritium $\beta$−spectrum with the unprecedented combination of a resolution of 0.93 eV at 18.6 keV and a transmission of 18% of $4\pi$ (Angrik et al., 2005). Operating with a windowless gaseous tritium source this spectrometer should reach, after 1000 days of data taking, the sensitivity to neutrino mass of 0.2 eV, ten times better than that of the best previous direct neutrino mass searches (Nakamura et al., 2010).

A long-term stability of the energy scale of the KATRIN spectrometer on a $\pm 3$ ppm level (i.e. $\pm 60$ meV at 18.6 keV) for at least two months is necessary since any unrecognized larger scale shift would result in an unacceptable systematic error of the neutrino mass derived (Kašpar et al., 2004). The retarding voltage of the spectrometer in the region of 18.6 kV will be measured continuously using a precision high-voltage divider (Thümmler et al., 2009). In addition, there will be an independent monitor spectrometer of the MAC-E-filter type, connected to the same high-voltage power supply as the KATRIN spectrometer. This monitor spectrometer will be adjusted to a sharp electron line satisfying the energy stability requirements mentioned above. The energy of this line should be close to the endpoint of the tritium $\beta$−spectrum, its stability will indicate the stability of the whole high voltage system.

In principle, solid state sources of internal conversion electrons, photoelectrons and Auger electrons could serve for the purpose, assuming that the natural width of the corresponding atomic shells will not exceed $\sim 4$ eV. This, together with the instrumental resolution of a few eV, is the necessary condition to resolve the zero-energy-loss peak in a measured electron spectrum. This peak corresponds to electrons that did not suffer any energy loss due to shake-up/off processes and/or inelastic scattering within the source material. In such a way, the peak energy is well-defined in the spectrum. The tested $^{83}$Rb/$^{83m}$Kr conversion electron sources with the 17.8 keV line of 2.7 eV width (Ostrick,

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2008; Vénos et al., 2010) almost fulfill the KATRIN requirements, but their production is not yet fully reproducible.

In this work, we investigate the feasibility of an energy standard utilizing photoelectrons ejected from the K atomic shell of a solid convertor by $\gamma$−rays. The half-lives of many excited nuclear states are longer than 1 ps. Therefore, $\gamma$−rays depopulating these states exhibit natural widths $\Gamma_\gamma < 1$ meV. This is the main advantage of $\gamma$−rays in comparison with X-rays, the natural width of which is of the order of units or tens of eV.

First, we considered commercial $\gamma$−ray sources of $^{241}$Am and $^{119m}$Sn irradiating Co and Ti convertors. Details of our calculations of the photoelectron rates can be found in Dragoun et al. (2010). Here, we extended the calculations for commercial $^{125m}$Te and $^{109}$Cd $\gamma$−ray emitters and Al and Mo convertors. In this way, we covered the range of photoelectron energies from 18 up to 80 keV. These quasi monoenergetic photoelectrons have an energy spread of 0.5–4.7 eV (see Eq. (2)). We also carried out several test measurements of the $^{241}$Am/Co photoelectron sources with electron spectrometers at Řež and Mainz laboratories. Details are described in Kašpar (2008).

## 2. Energy and width of the photoelectron lines

The kinetic energy of photoelectrons measured by a spectrometer is given by Siegbahn and Karlsson (1982)

$$E_{phe} = E_\gamma - E_{b,F} - \phi_{sp} - E_{rec}, \quad (1)$$

where $E_\gamma$ is the $\gamma$−ray energy, $E_{b,F}$ is the electron binding energy referred to the Fermi level of the metallic convertor, $\phi_{sp}$ is the spectrometer work function and $E_{rec}$ is the recoil energy. The Eq. (1) holds for the convertor conductively connected with the spectrometer. Chemical shifts of $\gamma$−ray energy are completely negligible in our application. A hydrocarbon contamination layer may slowly grow on the spectrometer electrode surface regardless of good vacuum conditions which may cause a change of the spectrometer work function $\phi_{sp}$. Thus the actual value of $\phi_{sp}$ has to be checked regularly during the course of the long-term experiment.

The width (sharpness) of the quasi monoenergetic photoelectron line, $\Gamma_{phe}$, can be expressed in the form

$$\Gamma_{phe} = \Gamma_\gamma + \Gamma_{vac} + \delta_{rec}, \quad (2)$$

where $\Gamma_\gamma$ is the natural width of the excited nuclear level depopulated by considered $\gamma$−rays, the $\Gamma_{vac}$ is the natural width of the corresponding atomic shell (Campbell and Papp, 2001) and the correction $\delta_{rec}$ accounts for the fact that the recoil energy of the atom (and thus also the photoelectron energy) depends on the emission angle of the photoelectron with respect to the photon direction.

In order to increase photoelectron intensity, a convertor with high atomic number $Z$ is preferable. On the contrary, low $Z$ is needed to keep $\Gamma_{vac}$ sufficiently small. We have chosen Co, Ti and Al convertors for the KATRIN purposes and a Mo convertor for higher photoelectron energies. For our values of $Z$ and $E_{phe}$ the correction $E_{rec}$ in Eq. (1) amounts to roughly 0.2–0.6 eV and the correction $\delta_{rec}$ in Eq. (2) varies between 0.05 and 0.35 eV. Exact values of these corrections depend on both the arrangement of the source and detector and on the spectrometer entrance angle.

Suitable radionuclides should have half-lives of at least several months and should not emit too much other $\gamma$- and X-rays that would increase the background in measured photoelectron spectra. Owing to low photoelectron yield from low-$Z$ convertors we need strong $\gamma$−ray sources. These sources must fulfill requirements for sealed radioactive sources, even in vacuum. Examining the available commercial products, we have chosen for the KATRIN purposes the $^{241}$Am source-type AMC13145, No. 1473 CW (Nuclitec, 2010) and the $^{119m}$Sn source-type MSn9.154 (Ritverc, 2010). For higher photoelectron energies, we have chosen the Ritverc sources of $^{125m}$Te and $^{109}$Cd. All the sources of activity 0.55–3.7 GBq were of a disc shape of about 8 mm in diameter and had a beryllium window for smaller attenuation of low-energy photons.

## 3. Calculations

### 3.1. Processes within the photoelectron source

Commercial $\gamma$−ray sources suitable for our purpose are usually composed of radioactive atoms incorporated in an inactive material closed in a metallic capsule with a beryllium exit window. A thin metallic foil serving as photoelectron convertor can be placed directly on the window. The arrangement of the photoelectron source is schematically shown in Fig. 1.

Some of the emitted $\gamma$−rays are absorbed in the source material or the exit window. Those that left the source can create photoelectrons in the convertor. Some of these photoelectrons exit the convertor without any energy loss. These are the zero-energy-loss photoelectrons that after passing energy analysis in a high-resolution spectrometer are represented as a quasi monoenergetic line in the measured spectrum. On the contrary, the

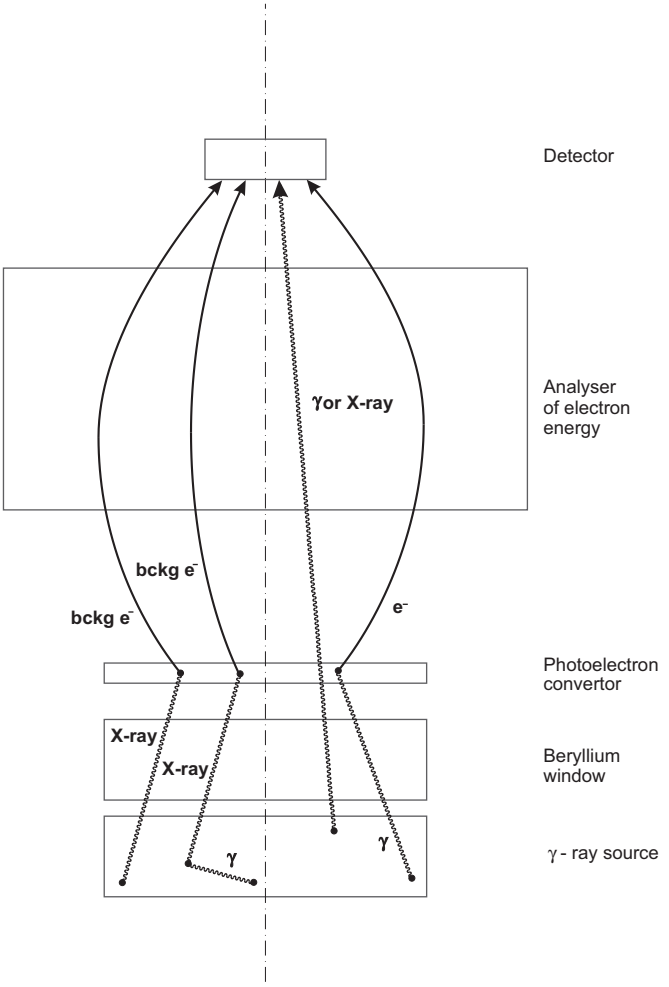


**Fig. 1.** Schematic arrangement of the photoelectron source, energy analyzer and detector. Several processes yielding useful and background photoelectrons are indicated (see Section 3.1). Not on a scale: in the case of the KATRIN monitor spectrometer, the detector solid angle for direct $\gamma$- and X-ray photons equals to $2.6 \times 10^{-7}$ of $4\pi$.