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K-SHELL IONIZATION PROBABILITIES OF Cu BY PROTON IMPACT AT ENERGIES OF 400 keV TO 600 keV

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Measurements of impact parameter dependent ionization probabilities for the K-shell of Cu by proton impact have been performed by detection of coincidences between characteristic X-rays and scattered projectiles. The use of the organic scintillator NE102A for X-ray detection drastically improved the timing resolution of the coincidence system compared to NaI(Tl) or Si(Li) detectors normally used. This made possible the measurement of 9 data points with experimental errors of 17-20% within accelerator times of 6-14 hours per data point.

The energy range (400-600 keV) and scattering angles of the projectiles (90°, 135°, 164°) have been chosen to investigate the influence of the recoil of the target nucleus on ionization probability. The experimental results are compared to theoretical predictions and agree with SCA-calculations if the recoil of the target nucleus is included.

In theoretical descriptions of inner shell ionization it has been realized that ionization can take place not only due to the interaction between the projectile and the target electron. The recoil of the target nucleus in an atomic collision process can have a strong influence on ionization probability. Calculations have been performed within the framework of the Semiclassical Approximation (SCA) [1,2,3] or by similar methods [4,5]. It can be seen from these calculations that the influence of target recoil on ionization probability is largest at small impact parameters and it can reduce ionization probability by a factor of 0.5 at low projectile energies.
The experimental observation of this effect therefore requires measurements at proton energies < 1 MeV and at large scattering angles (>90°) where scattering cross sections and ionization probabilities are low. When ionization probabilities are measured by detecting coincidences between characteristic X-rays and scattered projectiles, countrate is limited by the requirement that the number of detected true coincidences within the timing resolution $\Delta t$ of the coincidence system must be larger than the corresponding number of random coincidences [6]. Therefore long measuring times are required and only few data points have been reported in this regions of proton energies and scattering angles.

We have measured K-shell ionization probabilities of Cu at proton energies of 400-600 keV by detection of coincidences between characteristic X-rays and protons scattered into angles of 90°, 134° and 164°. Silicon surface barrier detectors (planar and annular) have been used for particle detection.

The organic scintillator NE102A was used for detection of the K X-rays of thin self supporting Cu targets, X-rays from outer shells were absorbed in an Al-coated mylar foil in front of the scintillator. Due to the superior timing properties of NE102A a timing resolution of 5 ns could be achieved compared to 22 ns measured with NaI(Tl).

Light output of NE102A is only 28 % of NaI (Tl). Due to this fact dark pulses of the photomultiplier tube and low intensity afterpulses of the scintillator could not be suppressed by energy discrimination as it is possible with NaI(Tl). This effect was investigated and its influence upon the detection efficiency of NE102A was determined by comparison of coincidence yields to those found with NaI(Tl). In our measurements 24 % of the detected X-ray pulses were due to delayed light emission.

The experimental results are shown in figure 1. The theoretical curves are SCA calculations done by Kocbach (method described in ref.[2]) including target recoil. As it can be seen there is agreement within the experimental errors of 17-20 %.

Figure 2 shows our K-ionization probabilities for 500 keV protons on Cu together with experimental results of Andersen et al. [6]. The solid and dashed lines are SCA calculations of Kocbach, with and without consideration of target recoil, respectively. There is a clear evidence that the recoil effect must be included to obtain agreement between experimental data and theoretical prediction.
Fig. 1. K-shell ionization probabilities of Cu by protons of 400 keV, 500 keV, 600 keV. The solid curves are SCA calculations done by Kocbach (method in ref. [2]).

Fig. 2. Comparison of K-shell ionization probabilities of Cu by protons of 500 keV to SCA calculations with (solid line) and without (dashed line) consideration of target recoil (Kocbach, ref. [2]).