Production of the isotope copper-64 by using natural nickel target with proton energy 17 MeV and beam current 10 µA at cyclotron

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Abstract. A calculation method is developed for production of the copper-64 isotope from the $^{64}$Ni(p,n)$^{64}$Cu nuclear reaction. The $^{64}$Cu radioisotope used in nuclear medicine is produced by irradiating a natural nickel target with a proton beam produced on a cyclotron. The conditions of the production were dictated by the capabilities of the cyclotron. The energy of the protons was 17 MeV (the beam current is 10 µA). As a result, the activity of copper-64 isotope for various irradiation times were obtained. The depth of proton penetration into the target material was studied.

1. Introduction
As known, nuclear medicine is based on the use of a variety radiopharmaceuticals, created on the basis of radioisotopes. Copper isotope $^{64}$Cu is unique, since in the process of radioactive decay it can emit $\beta^+$ (0.65 MeV, 17.5%), $\beta^-$ (0.57 MeV, 38.5%) particles, and Auger electrons. Therefore, this isotope can be used both in positron emission tomography (PET) and for radionuclide therapy [1,2]. The great advantages of this isotope over other isotopes are not only its chemical properties, but also a long half-life (12.7 h), which makes it easier to obtain, transport and use radiopharmaceuticals labeled with it, compared to those widely used at present.

$^{64}$Cu has numerous advantages over the PET isotopes $^{18}$F ($t_{1/2}$= 109.8 min) and $^{11}$C ($t_{1/2}$= 20.4 min) currently used in clinics. Since the half-life of both $^{18}$F and $^{11}$C is relatively short, these isotopes are usually prepared on cyclotrons located near clinics. In addition, the preparation of radiopharmaceuticals requires the preliminary isolation of radioisotopes and their further attachment by a molecular carrier, which requires additional special equipment [3].

Isotope $^{64}$Cu can be produced in nuclear reactors by the capture of either thermal neutrons $^{63}$Cu(n,γ), or fast neutrons $^{64}$Zn(n,p). Currently, for the production of $^{64}$Cu there are two cyclotron methods. One is based on $^{64}$Ni(p,n) and the other is based on $^{68}$Zn(p,αn) [4,5].

2. Method of calculations
This report presents the results of calculation for $^{64}$Cu production by using a proton beam energy 17 MeV (beam current 10 µA) to produce $^{64}$Cu at the MGC-20 cyclotron of “SPbPU”. The target is a natural mixture of nickel isotopes (the percentage of the $^{64}$Ni isotope in natural nickel is 0.926%).
The calculations take into account the loss of proton energy for excitation and ionization when passing through the target material [6].

\[ \left\langle -\frac{dE}{dx} \right\rangle = \left( \frac{KZ\rho}{A\beta^2} \right) \ln \left( \frac{2m_ec^2\beta^2}{I} \right) \]  

(1)

Where \( dE/dx \) is the mean rate of energy loss (MeV/cm); \( x \) is the path traversed in the target material or the depth of the target (cm); \( Z \) is the atomic number of the target; \( A \) is the atomic mass (g/mol); \( \rho \) is the target density (g/cm\(^3\)); \( m_e \) is the electron mass (g); \( c \) is the speed of light (m/s); \( \beta = v/c \) is the ratio of the speed of the projectile to the speed of light and \( I \) is the mean excitation energy (eV).

The production of \(^{64}\text{Cu}\) is carried out due to the reaction \(^{64}\text{Ni}(p,n)^{64}\text{Cu}\). The excitation function of this nuclear reaction has been measured in many experiments. In this paper, we used the result of combining the experimental data presented in the paper [7]. Using the solution of equation (1), we pass to the dependence of the cross section on the depth \( \sigma(x) \). The production of \(^{64}\text{Cu}\) at different depths in the target will be determined by the equation:

\[ \frac{dN_{\text{Cu64}}}{dx} = \left( \frac{Jn_{\text{Ni64}}}{\lambda e} \right) \left( 1 - e^{-\lambda t_{\text{irr}}} \right) \sigma(x) \]  

(2)

Where \( N_{\text{Cu64}} \) is the number of \(^{64}\text{Cu}\) nuclei; \( J \) is the beam current (A); \( n_{\text{Ni64}} \) is the concentration of \(^{64}\text{Ni}\) nuclei in natural nickel (cm\(^{-3}\)); \( \lambda \) is the decay constant of \(^{64}\text{Cu}\) (s\(^{-1}\)); \( e \) is the electron charge (C) and \( t_{\text{irr}} \) is the irradiation time (s).

Integrating (2) from zero to the target thickness, we obtain the dependence of the \(^{64}\text{Cu}\) production from zero to the target thickness \( \tau \):

\[ N_{\text{Cu64}}(\tau,t_{\text{irr}}) = \int_0^\tau dx \left\{ \frac{dN_{\text{Cu64}}}{dx} \right\} \]  

(3)

The solution of equation (1) is shown in ‘figure 1’ for protons energy of 17 MeV and natural nickel target. It can be seen that the optimal depth for stopping protons and losing all their energy is 0.056 cm.

**Figure: 1.** Solution of equation (1) for the proton energy \( E(x) \) with a kinetic energy of 17 MeV in a natural nickel target.
The ‘figure 2’ shows the dependence of the cross section for the $^{64}\text{Ni}(p,n)^{64}\text{Cu}$ reaction on the target depth.

![Figure 2](image)

**Figure: 2.** The dependence of the cross section for the $^{64}\text{Ni}(p,n)^{64}\text{Cu}$ reaction on the target depth. The bands are the errors in the determination of nuclear cross section.

The ‘figure 3’ shows the results of calculating the depth distribution of the weight of $^{64}\text{Cu}$ for different irradiation times from 0.5 to 2 hours and for different target thickness.

![Figure 3](image)

**Figure: 3.** The depth distribution of the weight of $^{64}\text{Cu}$ for different irradiation times and for different target thickness; (1) – 0.5 hour; (2) – 1 hour; (3) – 1.5 hours. The line indicates the dependences, and the band indicates the error associated with the error of the cross section for the $^{64}\text{Ni}(p,n)^{64}\text{Cu}$ reaction

Using equations (1) and (3) and the reaction cross sections given in [7], the activity of $^{64}\text{Cu}$ was determined using protons with an energy of 17 MeV, a current of 10 µA, and a natural nickel target.

In ‘figure 4’ shows the results of calculating the activity of produced $^{64}\text{Cu}$, for various irradiation times.

![Figure 4](image)

**Figure: 4.** The activity of $^{64}\text{Cu}$ produced for various irradiation times; (1) – 0.5 hour; (2) – 1 hour; (3) – 1.5 hours. The line indicates the dependences, and the band indicates the error associated with the error of the cross section for the $^{64}\text{Ni}(p,n)^{64}\text{Cu}$ reaction.
From the calculated results, table 1 was obtained, and the radioactivity of $^{64}$Cu was shown at a target thickness of 500 microns for different irradiation times.

**Table. 1.** The activity (Bq) of $^{64}$Cu after various irradiation times.

| Radioisotope | After 0.5 hours of irradiation | After 1 hour of irradiation | After 1.5 hours of irradiation |
|--------------|--------------------------------|-----------------------------|--------------------------------|
| $^{64}$Cu     | 2.8x10^7                      | 5.4x10^7                    | 8x10^7                        |

To calculate the activity of the radioisotope after the end of the irradiation time and after waiting various time, we can use the following equation:

$$A = A_0 e^{-\lambda t}$$  \hspace{1cm} (4)

Where $A$: is the activity of the radioisotope at time $t$ (Bq),

$A_0$: is the activity of the radioisotope at $t = 0$ (Bq),

$t$: the time (s),

$\lambda$: is the decay constant for $^{64}$Cu ($\lambda = (\ln2)/t_{1/2} = 1.52.10^{-5}$ s$^{-1}$).

3. **Summary**

In this work, a technique has been developed and a calculation has been carried out for production the $^{64}$Cu isotope, which is important for nuclear medicine applications, by irradiating a natural nickel target with a proton beam (17 MeV, 10 $\mu$A) obtained at the MGC-20 cyclotron. Thus, we see that the maximum yield of the $^{64}$Cu product is achieved with a target thickness of 0.056 cm. The activity of $^{64}$Cu produced was calculated for different irradiation times.

**References**

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