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EVALUATION OF ^{40}K NUCLEAR DECAY DATA, VIA MODEL NUCLEAR PROJECTILES

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ABSTRACT

The nuclear decay data of ^{40}K have been evaluated in this study via model nuclear projectiles. The reactants were carefully identified with the aid of KarlsruherNuklidkarte with the target nucleus in order to obtain the residual nuclide (^{40}K) and liberating the ejectile particle or in multiple. The liberation of ^{40}K in the study via all the reactions channels was based on production routes initiated and balanced to give $^{45}Cr\left(n,2\beta^{+}Pn\right)^{40}K$, $^{46}Mn\left(n,Li2P\beta^{+}\right)^{40}K$, $^{37}Ar\left(\alpha,P\right)^{40}K$, $^{42}Sc\left(\beta^{-},2n\right)^{40}K$, and $^{49}Ni\left(2\beta^{-},2\alpha2\beta^{+}\right)^{40}K$. Multiple tasks were performed with; EXFOR, Nucleonica, KAERI, CSISRS, Nudat especially compatibility of the decay data with their specifications in order to achieve theoretical cross section calculation data. The calculated Q-Values and Threshold energies were determined from the nuclear reactions and subsequently the excitation functions. Further empirical approach is encouraged in bids to realize more potential pathways of decay data of ^{40}K. Finally, the experimental study of this result is expected to unveil more insights. Their potential outcome this study is expected to address human quests in nuclear medicine, nuclear energy and nuclear arms against insecurity and military aggressions.

1.0 Introduction

Due to increasing human quest to diversify approach of accomplishments, nuclear decay has long enabled nuclear scientists to figure out useful data for advancement of human endeavors in different facets of life. From the elementary models of the nucleus to the highly advanced nuclear codes, nuclear decay remains evidenced in itself that the process of nuclear synthesis must be initiated by the spontaneous decay of the nucleus of the atom [1] and [2]. This synthesis of nucleus is an embodiment of data that have been studied and documented to involve nuclear data. ^{40}K, being the focal concern of previous studies, was found to occur primarily as a soft, silver-white metal forming an important constituent of the soil [3].

Evaluation of nuclear decay data of ^{40}K using the available nuclear projectile to combine with the proposed nucleus in order to achieve suitable and balanced nuclear reactions was achieved here. Target nucleus of various reactant will be employed to achieving theoretical calculations.

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A vivid account ofthe projectile particles and the ejectiles will be evaluated from the nuclear reaction cross section using the EXFOR code, Nudeonica, Nudat 3.2 etc. In a bid to achieving this, nuclear decay data parameters will be used to determine either an exothermic or endogenic nuclear decay.In this study, discussions on nuclear reaction models such as optical model, liquid drop model, phenomenological optical model potential, level density, statistical emission, pre-equilibrium emission model and exciton model have been considered similar to Umar and Ahijjo[4].

Figure 1: Schematic illustration of a projectile target interaction [5]

However, this study will be void of experimental and laboratory endeavors due to none availability of nuclear laboratory with adequate facility that could support the study and strenuous financial implications in a similar fashion to the study of Qian and Ren [6].

Energy conversion that may lead to existence of a new nuclide, it becomes imperative to employ mass defect, binding energy, Q-Value, and chiefly the reaction cross section to achieve calculations involving it.

Intuitively, the nuclear reaction could be positioned in order to simplify this concept. The main features being so dramatic and often termed as reactions that are initiated by projectile and a target as shown in Figure 1 [7].

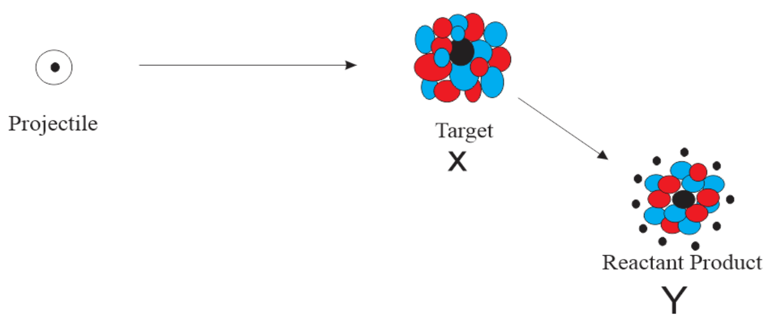
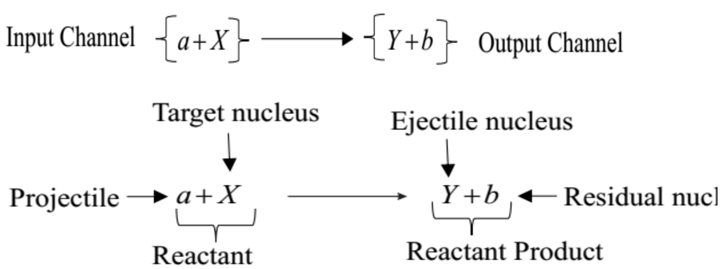


Figure 2: Schematic illustration of a projectile target interaction [5]

Just as the work conducted by U. S. DOE [8], the result of the model illustration above may be the mutation of the target thereby liberating a new particle or disintegration of the target as show in figure 2. For a glimpse of things, nuclear reaction could be represented in the following ways (see equation 3 and 4).



(3)

(4)

Nuclear reaction is a representation of an extremely dynamic phenomenology, due to this, adequate means must be devised for tracking and identifying reaction paths. For instance; when $a = b$ and $Y = X$ the expectation could be somewhatsimilar to equation 5;

$$a + X \rightarrow Y + b \quad (5)$$

This kind of reaction is described as the fusion of the scattering. Moreover, if Y and b are produced in the ground states, the scattering is called elastic scattering which is shown in the illustration of figure 3.

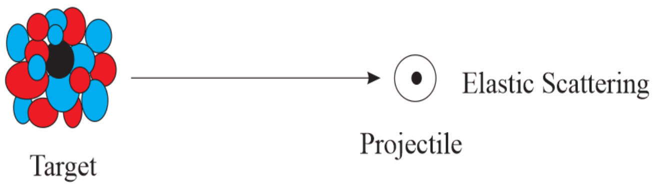


Figure 3: Illustration of elastic scattering [5]

While it is termed inelastic if the products are generated in an excited state of the interaction of the schematic illustration given in (3). But the interaction could lead to a nuclear capture rather known as radiative capture if the target nuclide engulfs the projectile, thereby capturing it for a significant duration. Due to the probabilistic nature of nuclear interactions, one of the energetic emissions majorly involves gamma-ray (γ) as illustrated infigure 4 is achieved.

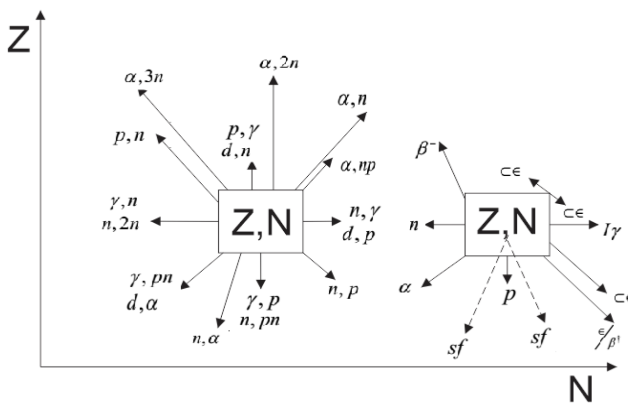


Figure 4: Illustrative diagram of radiative capture [5]

Shifting from a mere reaction involving reactants and products to an enormous fascinating nuclear reaction. In another dynamics for instance $Y \neq X$, i.e distinctiveness, the reaction turns transmutative, since a change has occurred in both the nuclear and atomic compositions. Hence, a channel is given from Figure 5.

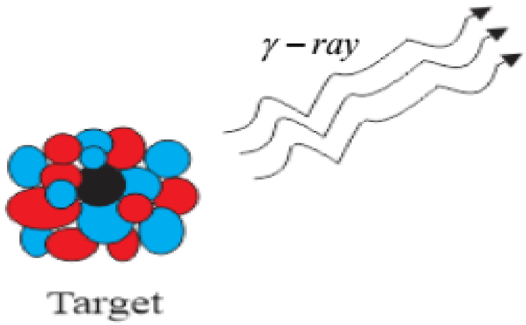


Figure 5: Chart of all emission pathways in nuclear reaction [5]

One important point to note is that several pathways are anticipated in any impact between a projectile and the target (see illustration in figure 5). For the sake of illustration from above idea, the collision of a neutron with an ^{27}Al could lead to the emission of an $\alpha -$particle and a proton with residual nuclide of ^{24}Na and ^{27}Mg

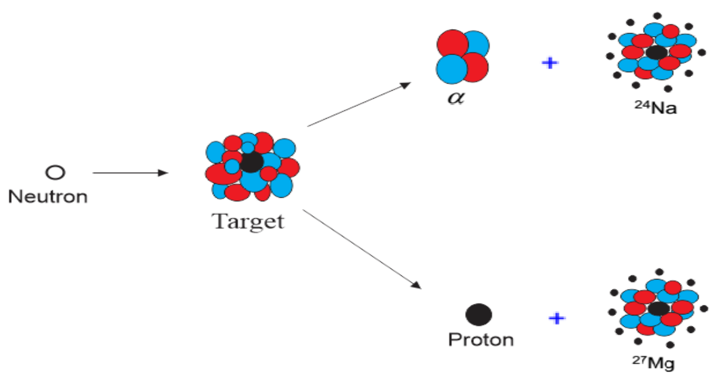


Figure 6: Chart of all emission pathways in nuclear reaction [5]

Each illustration above reaction channels is peculiar and probable in occurrence according to the law of quantum mechanics which may not be broadened here.
Nevertheless, Nuclear decay data should answer questions such as; how much or what amount of energy is required to trigger or initiate a nuclear reaction? This question is virtually difficult and out of the scope here. This is only possible if and only if the reaction has been theoretically initiated and carefully balanced to accurately undertake calculation of its reaction kinetics viz:

- Reaction Q-Value
- Threshold energy

Beginning from the energy conservation law on the input channel and the output channel as given in equation 6.

$$\underbrace{a+X}_{\text{Input Channel}} \longrightarrow \underbrace{Y+b}_{\text{Output Channel}} \tag{6}$$

Equation 6 is the precursor to equation 7 i.e., the Q-value being the variation of the rest energy of the particles.

$$Q=\left[(m_a+m_X)-(m_b+m_Y)\right]c^2 \quad (7)$$

If $Q>0$, the process occurs spontaneously otherwise $Q<0$ or $Q=0$, the reaction takes place when energy is introduced from the surrounding i.e., exploiting the kinetic energy of the projectile.

One other important quantity to be obtained from the energy analysis of a nuclear reaction is the minimum kinetic energy that the projectile must have before triggering the nuclear reaction[9]. This is called the threshold value of the reaction given in equation 8.

$$T_{\Delta gy} = (-Q)\frac{m_Y + m_b}{m_Y + m_b - m_a} \qquad (8)$$

For $Q > 0$, the reaction can occur at a very low energy range, but how much low? Is essentially a quest out of this study. Well, if the projectile is a nuclide particle such as the neutron, then the reaction can be triggered even as low as the energy corresponding to the motion of thermal agitation. This is an aspect of nuclear Physics that exposes all of us to the danger of nuclear reactions. This simply means that everyone is relatively receiving some doses of radioactive emission even at a very low energy.But if the projectile is a charged particle, such as proton, or $\alpha-$particle, then it must overcome Coulombic repulsion barrier generated by the nucleus as illustrated in figure 7 [1].

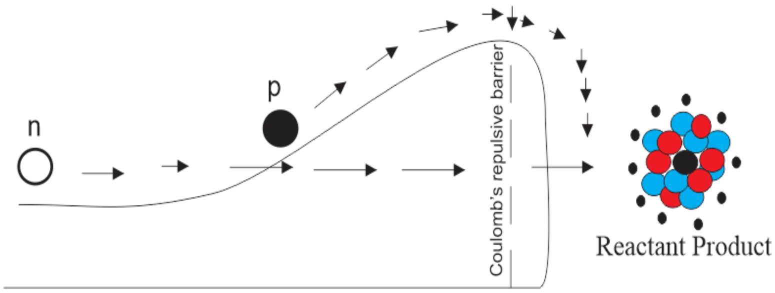


Figure 7: Illustration of two distinctive reaction pathways [5]

One major challenge is, how many nuclear reactions can take place? This may need some intuition to unravel. Intuitively, let us consider a situation whereby a projectile has to intercept a nucleus where it manifests its presence. Meaning that it is a matter of geometry according to Hauser-Feshbach Model [2]. See figure 8.

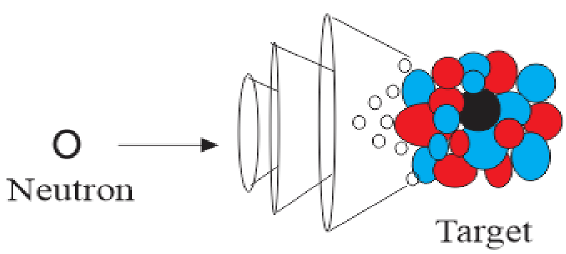


Figure 8: Illustration of a projectile intercepting target nucleus [5]

Figure 8 is an illustration the region in contes.. $1fm = 10^{-15}m$ .ell localized or distributed depending on the range of action of the phenomenological forces in the interaction. Consider the strong nuclear forces having a range of action of, as such, interaction region will have an extension very close to the physical radius of the nucleus. Moreover, it's possible to have a reaction depending on interaction time. in other word referred to as the collision time which is a function of its kinetic energy and other aspect of the quantum nature of the interaction which is intrinsically random. The entire nature of nuclear reaction must be handled with a probabilistic approach to adequately describe this phenomenon. Based on this, let's consider a very important physical quantity i.e., the reaction cross section.

Reaction Cross Section

Reaction cross section (σ) is related to the probability of interactions between the projectile and the target as illustrated in figure 9.

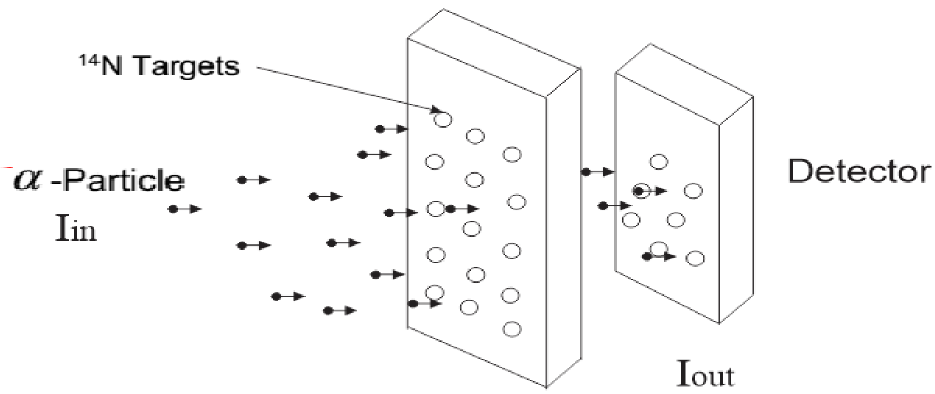


Figure 9: Illustration of reaction cross section [5].

But let us quickly consider an instance of a nuclear reaction below in equation 9.

$$\alpha + {}^{14}N \longrightarrow {}^{17}O + P \quad (9)$$

With cross section, we could understand detail of the physics involved based on the nuclear data calculations. The starting point is characterized by cross – sectional area 'A' having current I_{in} inserted in N nuclides of ${}^{14}N$ which can be detected by detector using the total current generated by the reaction. The σ corresponds to effective area 'A' offered by each target nuclide to the incident particle [10]. Therefore, N nuclei intersected by the incident beam of $\alpha-$particle offered a total area equal to;

$$\frac{N\sigma}{A} \quad (10)$$

Equation 10 is termed the interaction probability of a nuclear reaction. When above input is compared to the total area, it gives the relationship of equation 10. When identified by the current, it can be interpreted between 0 and 1, having the physical interpretation of interaction probability. In other word, this interaction probability corresponds to the ratio between current of the protons produced by the reactions and $\alpha-$ particle delivered to the target. These currents are measured during experiments leading to equation 11;

$$\frac{N\sigma}{A} = \frac{I_{out}}{I_{in}} \quad (11)$$

we may arrive at the desired reaction cross section as thus given in equation 12 derived from 11;

$$\frac{N\sigma}{A} = \frac{I_{out}}{I_{in}} \longrightarrow \sigma = \frac{I_{out}}{I_{in} \times \frac{N}{A}} \quad (12)$$

measured in bans1 ban = $10^{-24} cm^2$.

In 2016, Almas conducted a study of reactions of positron emitter at Government College University (GCU) Lahore, Pakistan, where the positron emitter's libraries were used to ascertain the Q-value and threshold energy calculations. Her work was employed for laboratory exercise later for itsexperimental outcome. Some of the major setback in her study was the lacking in any mention in cross section which determines the probability of the reaction occurring.

Also, the corresponding energies was required being it a neutron induced reaction. However, to overcome the areas that were found lacking in the work of Almas [7], this study shall explore the results of individual nuclear reactions undertaken with an emphasis on the nuclear data provided by IAEA monitored data in EXFOR.

Similarly, a related study was presented at the 3rd School of Physical Sciences Biennial International Conference by Ahijjoand Baba-Kutigi[2] on the theoretical nuclear data evaluation for the production of ^{64}Cu as a tool in PET & SPECT. They presented details of pathways of production of ^{64}Cu including the excitation function $^{64}Zn(n,p)^{64}Cu$ and was validated using the experimental Reaction data (EXFOR/CSISRS, 2012).

Methodology

From the concept of nuclear physics as earlier put forward byBernard, [11], The model nuclear reaction involving $^{45}_{24}Cr$ as the target nuclide was initiated taking $^{1}_{0}n$ as the projectile particle and used to penetrate the nucleus of the target nucleus to yield equation 15.

$$^{45}_{24}Cr + ^{1}_{0}n \; ^{40}_{19}K + 2\,^{0}_{+}\beta + 3P + ^{1}_{0}n \rightarrow \text{or}\; ^{45}Cr\left(n, 2\beta^{+}Pn\right)^{40}K \qquad (15)$$

In a similar and careful approach, $^{46}_{25}Mn$ was employed as the target nuclei and $^{1}_{0}n$ was used for the penetration of the nucleus of the target to yield ^{40}K. This model reaction was noticed to give additional residual nuclide of $^{5}_{3}Li$ while emission of excess protons and a positron were respectively acquired as shown in equation 16.

$$^{46}_{25}Mn + ^{1}_{0}n \; ^{40}_{19}K + ^{5}_{3}Li + 2P + \beta^{+} \rightarrow \text{or}\; ^{46}Mn\left(n, Li2P\beta^{+}\right)^{40}K \qquad (16)$$

In a somewhat diversified approach, a model nuclear reaction was obtained taking the target of $^{37}_{18}Ar$ whose nucleus was then reacted with a heavily charged α-particle. The reaction was balanced as given below in equation 17.

$$^{37}_{18}Ar + \alpha^{2+} \; ^{40}_{19}K + P \;\text{or}\; ^{37}Ar\left(\alpha, P\right)^{40}K \qquad (17)$$

An excess neutron emission reaction involving $^{42}_{20}Sc$ was however achieved even though such reaction posed some technical difficulties. They were overcome by identifying the possibility of accomplishing the reaction with β^{-} as shown below in equation 18.

$$^{42}_{20}Sc + \beta^{-} \; ^{40}_{19}K + 2\,^{1}_{0}n \;\text{or}\; ^{42}Sc\left(\beta^{-}, 2n\right)^{40}K \qquad (18)$$

The last nuclear reaction obtained was the reaction involving $^{49}_{28}Ni$ in which excess β^{-} enhanced the liberate ^{40}K under the heavy collections of ejectile particles. The nuclear equation showing this scenario is given in 19.

$$^{49}_{28}Ni + 2\beta^{-} \; ^{40}_{19}K + 2\alpha + 2\beta^{+} + n \rightarrow \text{or}\; ^{49}Ni\left(2\beta^{-}, 2\alpha 2\beta^{+}\right)^{40}K \qquad (19)$$

Q-Value & Threshold Energy Calculation

The Q-Value was calculated in this study being the required value of energy that must be absorbed or released for a nuclear reaction to take place. In this study, the Q-Value was determined using all the participating reactants and products given in equation 7 and 8. While the Threshold energy was used to ascertain data for the reaction involving target nuclides and projectiles so as to produce resultant residual nuclides and ejectiles. The values obtained for the Threshold energy were found greater than the Q-Value due to the fact that momentum during the interaction between the target and the projectile is conserved. The nuclear data and information used were obtained the from listsof platforms mentioned in the results and discussion section that follows.

Results and discussion

The results obtained in this study were mainly validated by utilizing the information on Nudat 2.0, 3.0, EXFOR 3.2, KAERI Nuclear Data Center, CSISRS– Pakistani Version, Nucleonica Nuclear Code and KarlsruherNuklidkarte of the European Commission Joint Research Centre, Institute for Trans-uranium Elements - 2006-2007 Revised edition. All the nuclear reactions that could give characteristic excitation function were trashed out. The evaluation was based on the potential fittings which produces the functions of figure 10 to 14 respectively [12].

Evaluation of $^{45}Cr\left(n,2\beta^{+}Pn\right)^{40}K$ Reaction

^{45}Cr is a fairly stable isotope of Cr. Information from Majill et al [1] is that ^{45}Cr takes part in $(n,2\beta^{+}Pn)$ reactions which has shown high tendency of yielding a stable radioisotope of ^{40}K in this study. However, no experimental data of such reaction was readily available prior this study. Making this result a breakthrough if the experimental data could be harnessed in future. It is noteworthy that the range of energy earlier chosen for low energy nuclear reaction in the theoretical approach led to the characteristic excitation function of the reaction (see the illustration in figure 10). A similar study was reported on the significant of nuclear evaluation earlier by Kastleiner, [13].

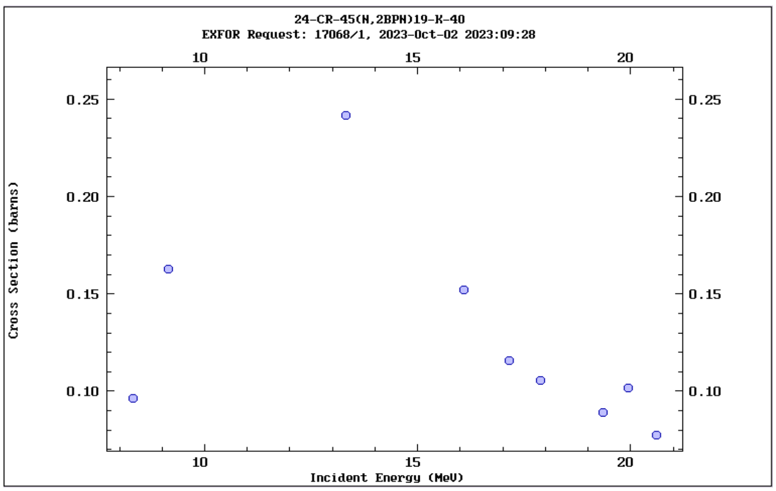


Figure 10: Excitation function of $^{45}Cr\left(n,2\beta^{+}Pn\right)^{40}K$ reaction.

Evaluation of $^{46}Mn\left(n,Li2P\beta^{+}\right)^{40}K$ Reaction

In a similar dimension, ^{46}Mn was noticed with impressive feature for taking part in a nuclear reaction that liberated ^{40}K prior subjecting our outcome into expensive laboratory endeavours. The products of $(n,Li2P\beta^{+})$ reaction gave a promising feature of positron emission which is often sort over in the nuclear technology due to enormous relevance attached to it. Based on that, more energy is required as shown below. Similar trends could be noticed between the excitation function of $(n,Li2P\beta^{+})$ and $(n,2\beta^{+}Pn)$ reaction channels (see figure 11).

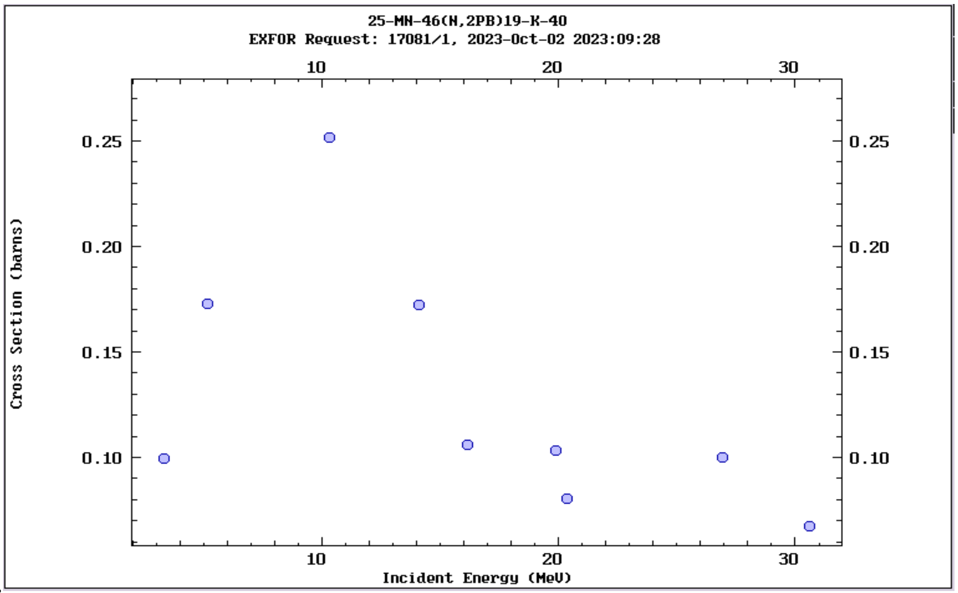


Figure 11: Excitation function of ${}^{46}Mn\left(n, Li2P\beta^{+}\right){}^{40}K$ reaction.

Evaluation of ${}^{37}Ar\,(\alpha, P)\,{}^{40}K$ Reaction

Since the reactions in nuclear dimensions are often employed in predicting outcomes and behaviors of probabilistic results, the reaction channel of (α, P) was found with something strange. It was surprisingly noticed to be compatible by yielding a proton which is much predicted. The implication was the desire of more energy in order to accomplish the reaction.

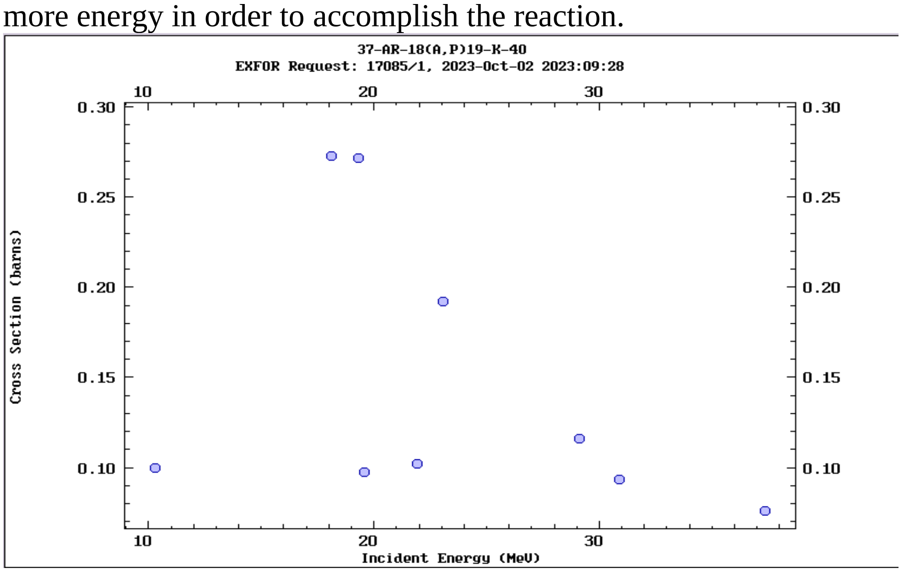


Figure 12: Excitation function of ${}^{37}Ar\,(\alpha, P)\,{}^{40}K$ reaction.

The characteristics excitation function of the two previous reactions could be noticed to operate on a lesser amount of energy range. Since α - decay is often achieved fairly at about $25\,MeV$ or above. Hence features exhibited by the characteristic excitation function in figure 12 are in good agreement with potential predictions of this study on the energy requirement for an α - decay.

Evaluation of $^{42}Sc\,(\beta^-,2n)\,^{40}K$ Reaction

The reaction channel $(\beta^-,2n)$ was achieved with a somewhat dynamic feature even though a fairly similar range of energy was maintained. Excess neutrons were liberated in the process with the residual nuclide of ^{40}K. The target nucleus ^{42}Sc was assumed to exhibit internal conversion $(I\gamma)$ but rather yielded excess neutrons. The excitation function is given below in figure 13.

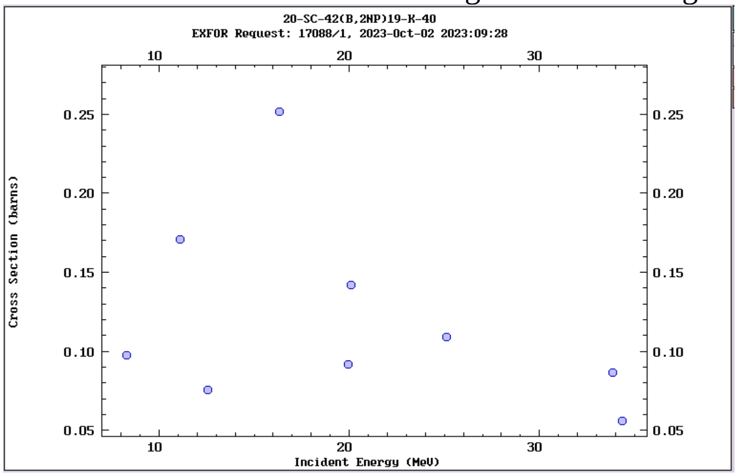


Figure 13: Excitation function of $^{42}Sc\,(\beta^-,2n)\,^{40}K$ reaction.

Evaluation of $^{49}Ni(\,2\beta^-,2\alpha 2\beta^+)\,^{40}K$ Reaction

Figure 14 below is an incident energy cross section characteristic of ^{49}Ni. It is among the numerous

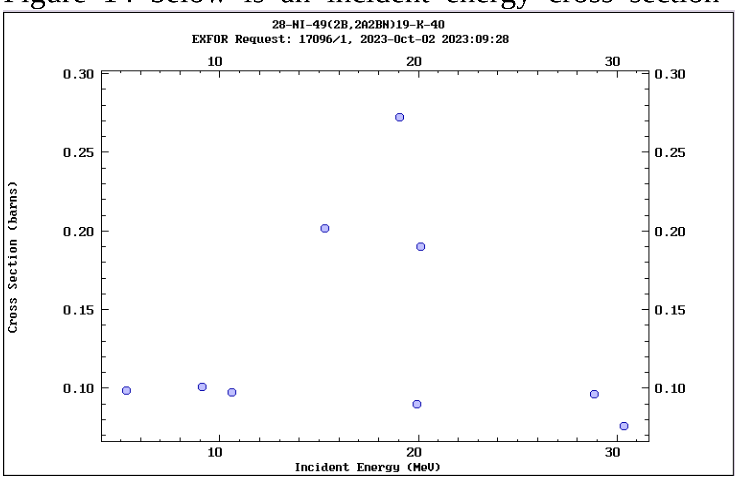


Figure 14: Excitation function of $^{49}Ni(\,2\beta^-,2\alpha 2\beta^+)\,^{40}K$ reaction.

fairly stable radioisotopes of Ni. Majill et al [1] have it that ^{49}Ni takes part in $(\,2\beta^-,2\alpha 2\beta^+)$ reactions to liberate β^+ with a high tendency of yielding a stable radioisotope of ^{40}K.

However, no experimental data of such reaction is presently available on EXFOR, Nudat, KAERI and CSISRS. This is another significant aspect of this study similar to that of Qaim, [14].

Conclusions

All the nuclear reactions performed did achieve parameters for calculations as well as predictions on how we could potentially obtain the evaluation of ^{40}K via the model nuclear equations. The decay data from these reactions were also availed us excitation functions as earlier stated above. The calculations have adequately broadened the chances of performing the cross section of the reactions. One of the main striking features of the decay data of ^{40}K were the accuracy achieved in the calculations from the nuclear reactions.However, the results of this evaluation were achieved reaction channels leading to the emission of ^{40}K were adequately achieved as earlier outlined in the synopsis. Also, the theoretical calculations were aided by EXFOR, Nucleonica, and KAERI approved by IAEA. Hence, the calculations were based on the data accessed from aforementioned channels. The decay modes were determined from an authentic source information. A reliable calculation of Q-Value was performed with the aid of data obtained from KAERI and also used to ascertain the Threshold energy of each reaction. The utility outlets of EXFOR were very supportive in cross section and the excitation function of the reactions. The reactions have adequately availed information on the decay modes of all the reactions except the discarded nuclear equations.

The results obtained in this study is crucial for understanding and prediction of nuclear reactions decay data and hence, it is recommended for optimization in relevance to nuclear medicine and nuclear energy generation [15].

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