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$^{16}O \rightarrow {}^{8}Be + {}^{8}Be$ Decay Simulation

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Abstract. The fact that the ^{4}He is one of the most strongly bound nuclei led to the discovery of α-clusters models in the nuclei. It is so stable that remains as a cluster in the ^{12}C, ^{16}O, ^{20}Ne, etc. The nuclei that for α-clusters called α-conjugate nuclei. ^{13}C (^{4}He, n) reaction was used to study α - cluster states in the ^{16}O excited levels. The measurements will improve knowledge of possible linear α-chain structure in ^{16}O. In this work, we will present angular distribution simulation results with Geant4 for ^{16}O-excited levels that were measured in the Ref. [8]. The simulated results will be used later on experimental data analysis that was carried out at the University of Notre Dame.

Keywords: Angular distribution, Geant4 simulation, α-cluster

1. Introduction

After the Big Bang only light nuclei (H, He and Li) were created. This nucleus has become a building block for synthesis of higher mass elements. The α-nucleus as a cluster component has been identified in α-conjugate nuclei that is nuclei with equal and even number of proton and neutrons. The special stability of the α nucleus or clusters of α particles continue to persist in heavier nuclei such as ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg and others [1]. Besides that ^{4}He is noble gas and interacts very weakly, first excited state of this nucleus is around 20 MeV. The binding energy of this nucleus is also very high compare to nearby nuclei [2]. Addition to this α-α strong and repulsive interaction coming from Pauli exclusion principle [3, 4], made α-cluster model. During 1960s multiply studies were done to revival the model [5, 6] and eventually in 1968 Ikeda suggested the structure of α clusters in the α-conjugate nuclei excited states [7].

One of the best example of nucleus that forms α-cluster is ^{16}O. Numerous experiments with different methods were done [1, 8-10] to study α cluster components in the structure of ^{16}O. This aspect of the ^{16}O structure is relevant for α-burning reactions thought to play a significant role in stellar evolution.

^{13}C(^{4}He,n) reaction was used to produce ^{16}O at the University of Notre Dame Nuclear Science Laboratory with 10.5 MV FN Tandem. Beam energy was in the range from 24 MeV to 29.2 MeV so the created ^{16}O will be above 4α breakup level. In that levels ^{16}O can decay with following channels: $^{16}O \rightarrow {}^{8}Be + {}^{8}Be$, $^{16}O \rightarrow {}^{12}C + {}^{4}He$ or $^{16}O \rightarrow 4\ {}^{4}He$. The measurements help to reveal the possible linear α-chain structure in ^{16}O. More details of the experimental results will be published.

Following paper shows the results for $^{16}O \rightarrow {}^{8}Be + {}^{8}Be$ channel simulations with Geant4 [11]. This simulations will be used to do angular momentum assignment. As isotropic distribution of ^{16}O was simulated it would be possible to find the states with 0^{+} angular momentum.

2. Simulation Method

Four 32 by 32 Double-sided Silicon Strip Detectors (DSSD) were used to measure charged particles energies and positions. DSSD were located symmetrically to beam direction. The detectors centers were 13 cm and 12 cm away from target with 23.8^{0} and 57.3^{0} angles relative to beam direction, respectively. It is important to use correct physics list in Geant4 simulations as well. In those simulations were used already existing “Shillding.hh” physics list [12]. That physics list includes best-guess selection of electromagnetic and hadronic physics processes.

As the goal is to study angular distribution of ^{16}O which breaks-up with $^{16}O \rightarrow {}^{8}Be + {}^{8}Be$ channel

after $^{13}C(^{4}He, n)$ reaction, the ^{16}O direction was randomized and picked up only the angles in which case all four α-particles were detected in the detectors.

^{16}O and neutron will have opposite directions in the center of mass frame as it is two body reaction. Angle between the ^{16}O and beam directions is center of mass θ angle. After randomizing ^{16}O direction the angle also will be random.

The energy approximation was done and non-relativistic case was used due to nuclei low energies. Energy and momentum of ^{16}O was calculated with the energy and momentum conservation laws after randomizing the angle.

The angular distribution should be *sine* function, due to solid angle dependence from center of mass frame θ angle (Eq. 1).

$$d\Omega = \sin(\theta) d\theta d\varphi \tag{1}$$

Comparison of isotropically simulated one million ^{16}O angles and solid angle function shown in Fig. 1. Constant "A" is the value when the angle was equal 90^0 so the *sine* function will be equal to one.

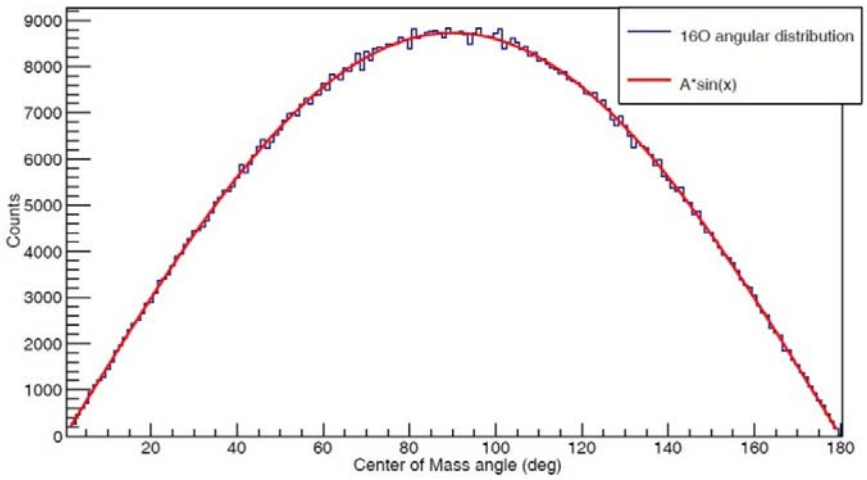

Fig. 1. Isotropically angular distribution of ^{16}O comparison with A*sin(x) function. Where A is a constant and equal to value of distribution when $x=90^0$.

Initial particles in the Geant4 were simulations after ^{16}O direction generation. In place of ^{16}O, two ^{8}Be should be generated.

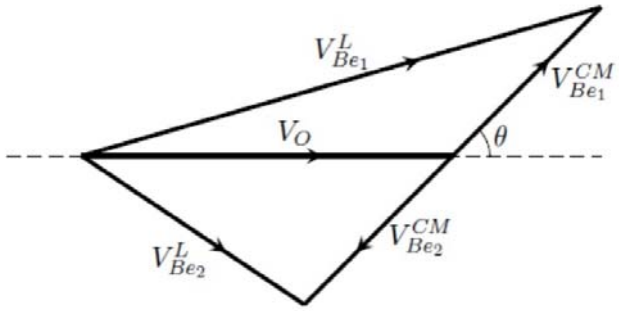

Fig. 2. Velocities diagram of ^{16}O and two ^{8}Be in the laboratory and center of mass frames.

In the ^{16}O related frame, ^{16}O will be in rest and two ^{8}Be will breakup with the same energy in opposite directions. In the laboratory frame ^{16}O, on the other hand, has a kinetic energy. So, again ^{16}O momentum and ^{8}Be center of mass momentum can form any angle, because ^{16}O can breakup isotropically. Generating random angle in this case as well, ^{8}Be momentum direction was calculated in the center of mass. Fig. 2 shows the diagram of ^{16}O and two ^{8}Be velocity diagram in the center of mass and laboratory frames. The vectorial sum of ^{16}O and ^{8}Be center of mass velocities will be equal to ^{8}Be velocity in the laboratory frame:

$$V_{Be_1}^{L} = V_0 + V_{Be_1}^{CM}; V_{Be_2}^{L} = V_0 + V_{Be_2}^{CM} \tag{2}$$

Initial energy of ^{8}Be in the center of mass frame can be calculated from excitation energy and Q-value of reaction which is Q = 14.62 MeV. As ^{16}O will be in rest in its frame, each ^{8}Be will get equal energy shown below:

$$E_{^8Be} = \frac{E_x + Q}{2} \tag{3}$$

With the Eq. 3, the kinetic energy can be calculated for each ^{8}Be after ^{16}O breakup. In the laboratory frame each ^{8}Be velocity can be calculated with equations below:

$$(V_{Be_1}^{L})^2 = (V_0)^2 + (V_{Be_1}^{CM})^2 + 2V_0 V_{Be_1}^{CM} \cos(\theta) \tag{4}$$

$$(V_{Be_2}^{L})^2 = (V_0)^2 + (V_{Be_2}^{CM})^2 - 2V_0 V_{Be_2}^{CM} \cos(\theta) \tag{5}$$

After calculating each ^{8}Be energy and momentum direction in the laboratory frame with the Eq. 4 and Eq. 5, both ^{8}Be were simulated. Then ^{8}Be will breakup into two α-particles.

3. Results

The nucleus in the 0^+ excited level after decays emits particles isotropically. In the simulation initial ^{16}O were generated isotropically, so after comparison can be predicted which states have 0^+ spin and parity. On the other hand, in the experimental results except from the channel of interest, ^{16}O can breakup with other channels as well and even after gates there still will be some residual background. That background, as well, will be distributed isotropically. So following simulations will help to subtract residual background, increase precision for angular distribution, and spin assignment.

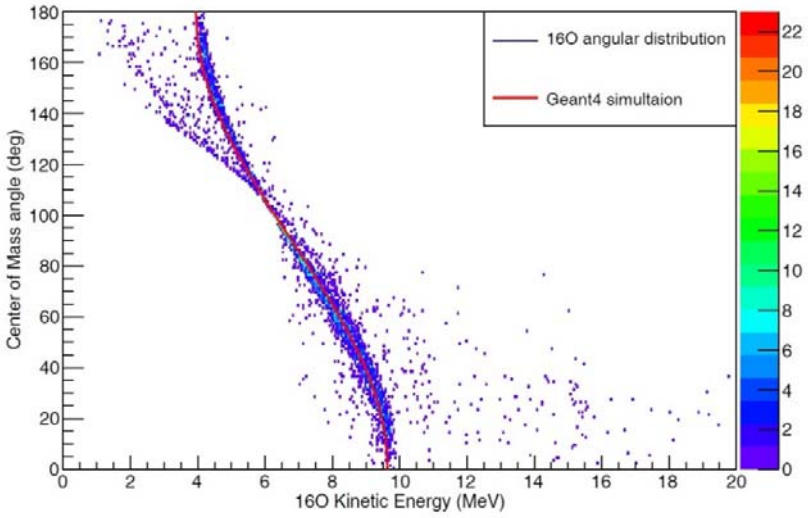

Fig. 3. Comparison of simulated and experimental ^{16}O kinetic energy and center of mass angle dependences.

First of all the kinematics of the simulation should be checked to be sure that the results from the simulation produce correct results. The simplest case is ^{16}O kinetic energy and center of mass angle relation, which can be calculated from any kinematic calculator.

The comparison of the experimental and simulated kinetic energy distributions is shown in the Fig. 3. In this case, 1 million ^{16}O were generated, but it was made a smooth line. The comparison shows that the simulated angular distribution match with the experimental distribution very well. Therefore, the kinematics in the simulation works correct.

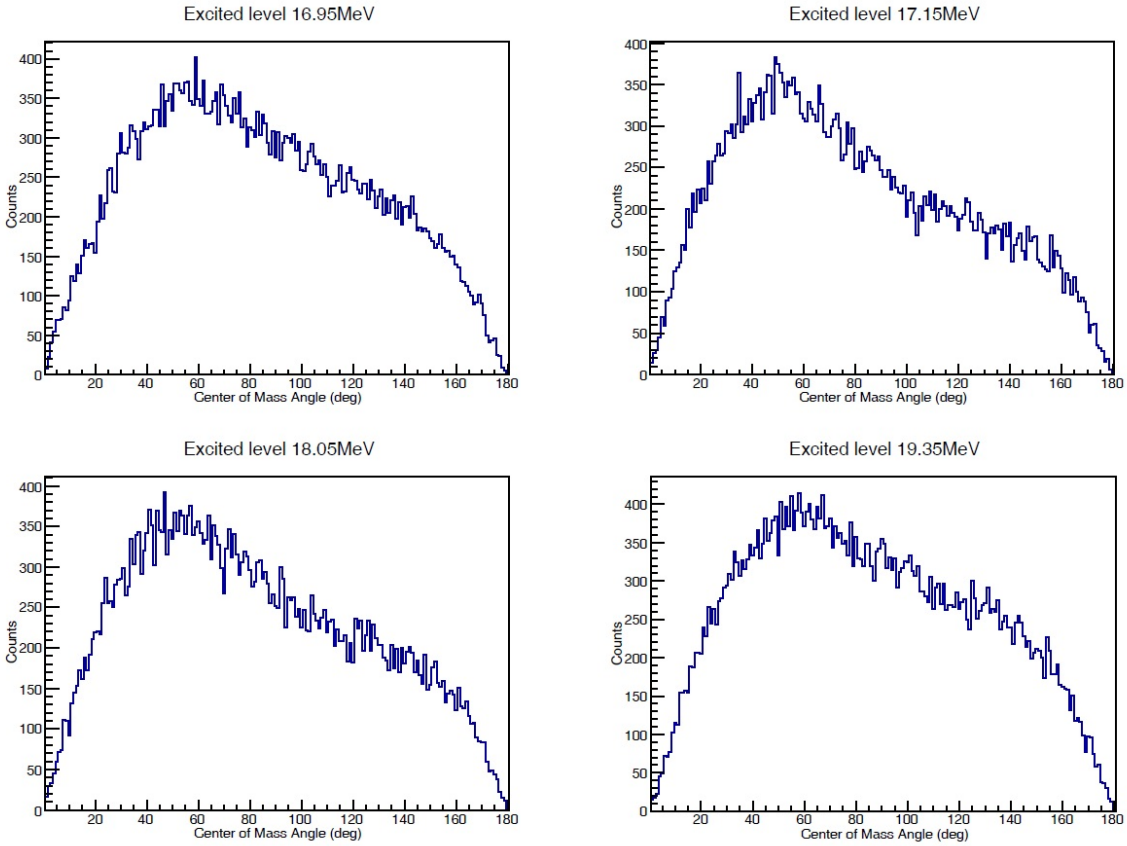

Fig. 4. Isotropic simulations for each excited energy level from Ref. [8]. Initially 1 million ^{16}O were generated.

Fig. 4 shows the angular distribution simulation for 4 excited levels. Again, in these simulations 1 million ^{16}O were generated initially for all levels. All states angular distributions have very similar structure, as for all of them ^{16}O were generated isotropically. The angular distribution of the state depends only from the spin and parity and does not depend on excited level energy.

4. Conclusion

The Geant4 simulation code is ready to be used. The simulation results will help to do important calculations during experimental data analysis. First of all, it will make possible to identify the excited levels with 0^+ spin and parity. Besides, it will make possible to produce isotropic background and do the experimental background subtraction.

Acknowledgement

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