NUCLEAR ASTROPHYSICS IN NPI ASCR ŘEŽ

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The U120M cyclotron in NPI ASCR, Rez, delivers light particle beams that can be used for different indirect methods to reach experimentally the Gamow region. ANC Asymptotic Normalization Coefficient method and THM Trojan Horse method are used to extract information on astrophysical S-factors in the above mentioned region. Key parameters of the U120M cyclotron are presented, a review of recent experiments concerning problems of nuclear astrophysics is given.

1. Introduction

Since the beginning of nuclear physics, the theory and experiment pushes the innovation and development of new accelerators that can reach deeper into still undisclosed nuclear landscape, discover new phenomena and bring deeper understanding. As the funding is always limited, an operation of older devices cannot be usually supported. However, it appears that devices that were not closed in the past, nowadays, they can be a useful tool for nuclear physics and in a sense complementary to large modern accelerators. One example is U120M cyclotron in NPI ASCR Řež.

The U120M isochronous cyclotron (Fig.1) was build in JINR Dubna and was put into operation in 1977, later, it has undergone several upgrades.

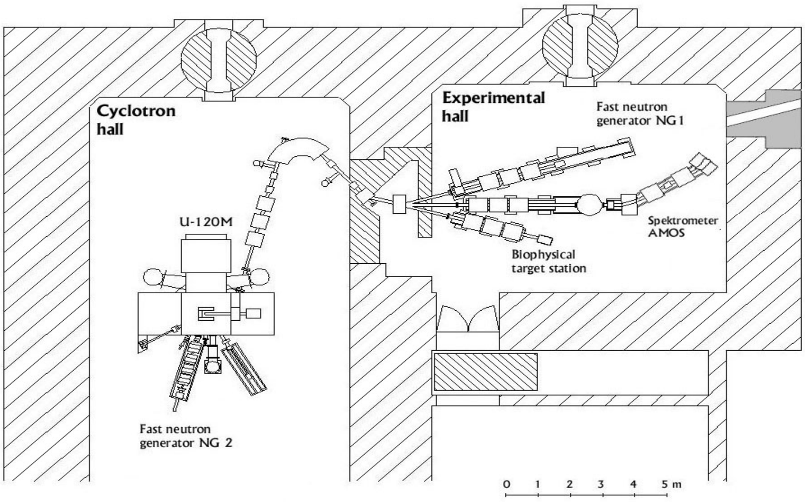

Fig.1. Cyclotron U120M and experimental lines

Available beams and intensities are shown (Table 1). Negative beams are extracted by stripping foil southward (Fig.1). Beam intensity extracted by deflectors (northward) is significantly reduced to typically a fraction of uA and the intensity of a collimated and final collimated mono-energetic beam is typically between 1-50 nA in experimental hall.

Table 1. Basic parameters of U120M cyclotron. The typical maximal intensity reached in the cyclotron cave.

beam	energy span [MeV]	maximal intensity
p -	10 – 38	40 uA
p +	10 – 25	5 uA
d -	10 – 20	25 uA
d +	10 – 20	5 uA
^{3}He+	17 – 53	2 uA
^{4}He+	20 – 40	5 uA

The ^{2}H and ^{3}He beam particles have well understood cluster structure, which fact has appeared very important for indirect methods that can be used to study nuclear reactions that are otherwise influenced by a strong Coulomb barrier.

These reactions have frequently certain astrophysical aspect and a compound projectile is used to deliver the particle of interest into the range of a strong interaction.

There are two indirect methods that are used in the U120M cyclotron experiments Asymptotic Normalization Coefficient method (ANC) and Trojan Horse Method (THM).

2. ANC method

The Asymptotic normalization coefficients method exploits the conditions of peripheral nucleon transfer. The diagram (Fig.2) schematically shows the transfer of the particle *a* from the projectile *x* to the target nucleus A.

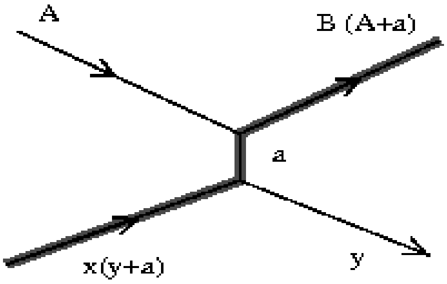

Fig.2. The diagram describing transfer of the particle a from the projectile x in ANC method

The (radial) overlap function I of the bound state wave function is usually approximated by a model wave function ϕ of the bound state

$$\alpha = (\beta\ \gamma) \qquad I^{\alpha}_{\beta\gamma l_\alpha j_\alpha}\left(r_{\beta\gamma}\right) = S^{1/2}_{\beta\gamma l_\alpha j_\alpha}\ {}_{n_\alpha l_\alpha j_\alpha}\left(r_{\beta\gamma}\right)$$

where *S* is the spectroscopic factor of the configuration ($\beta\ \gamma$). While the spectroscopic factor mainly reflects the overlap in nuclear interior, the dominant contribution to the peripheral reaction comes from the outer region of nuclei. The asymptotic behavior of the bound state wave function is described by Whittaker function *W*, $\kappa_{\beta\gamma}$ being the wave number of the bound state. This asymptotic behavior is the same as the asymptotic behavior of radial overlap function *I*:

$$ {}_{n_\alpha l_\alpha j_\alpha}\left(r_{\beta\gamma}\right) \to b_{\beta\gamma l_\alpha j_\alpha} \frac{W_{-\eta_\alpha, l_\alpha + 1/2}\left(2\kappa_{\beta\gamma} r_{\beta\gamma}\right)}{r_{\beta\gamma}} \qquad r_{\beta\gamma} > R_N $$

$$ I^{\alpha}_{\beta\gamma l_\alpha j_\alpha}\left(r_{\beta\gamma}\right) \to C^{\alpha}_{\beta\gamma l_\alpha j_\alpha} \frac{W_{-\eta_\alpha, l_\alpha + 1/2}\left(2\kappa_{\beta\gamma} r_{\beta\gamma}\right)}{r_{\beta\gamma}} \qquad r_{\beta\gamma} > R_N $$

The parameter *C* determines the amplitude of of the radial overlap function tail and is called the asymptotic normalization coefficient.

The cross section in the conventional DWBA, that is parametrized as a product of spectroscopic factors *S* can be - for peripheral transfer – rewritten as

$$ \frac{d\sigma}{d\Omega} = S_{Aal_B j_B} S_{Yal_x j_x} \sigma^{DW}_{l_B j_B l_x j_x} \to \Sigma_{j_B j_x} \frac{\left(C^{B}_{Aal_B j_B}\right)^2 \left(C^{X}_{Yal_x j_x}\right)^2}{b^2_{Aal_B j_B} b^2_{Yal_x j_x}} \sigma^{DW}_{l_B j_B l_x j_x} $$

One important difference is that the modification of DWBA analysis (that takes into account the correct normalization of the peripheral parts of the cross sections) results in very weak or no dependence of the ANC on potential geometry. This diminishes one important source of uncertainties. In comparison to direct methods, this method gives access to the physical data at low energies without an extrapolation.

ANC's are related to nuclear vertex constants that are graphically represented as vertexes (Fig.2). Each vertex actually corresponds to direct radiative capture process and one vertex is in our case of experiments on U120M with d or ^{3}He projectiles already known.

Detailed description of the method can be found in ref. [1,2,3] and references therein. The method was introduced by A.M.Mukhamedzhanov in NPI ASCR and tested in common experiments with TA&MU group.

3. THM method

While the ANC method can be used to extract the absolute value of the astrophysical S-factor for direct capture reactions, the THM can probe the energy dependence of the low-lying resonances in very low-energy region. It can be applied to two-body reactions by using three-body break-up reactions and a cluster nature of the projectile. In this way it is possible to overcome Coulomb barrier of the entrance channel.

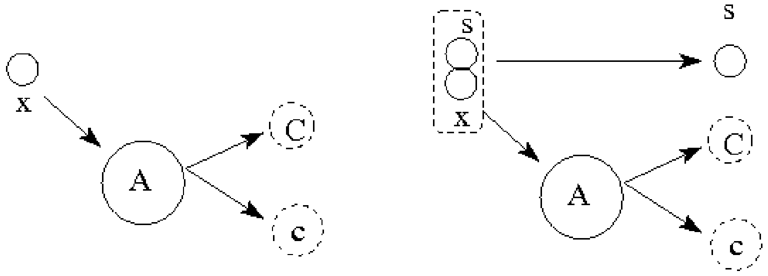

Fig.4. Schematical diagram of the THM principle. Two-body reaction under focus (left), cluster containing the projectile and spectator parts overcomes the Coulomb barrier (right).

For carefully selected three-body reaction partners and parameters and selection of proper kinematical conditions, only one part of the projectile-cluster interacts with the target nucleus and the remaining part of the cluster behaves as a spectator. So called quasi-free contribution of the three-body reaction is extracted to obtain access to two-body sub-process.

The complete kinematics of the three-body process must be determined, which means the detection of two out of three outgoing participants. The cluster binding energy inside the projectile allows to reach low energy relative energy of the two-body reaction.

The two-body reaction cross section can be extracted from the data using PWIA theoretical approach:

$$\frac{d^3\sigma}{dE_c d\Omega_C d\Omega_c} \approx KF|\varphi(p_s)|^2 \frac{d\sigma}{d\Omega}(E_{A-x}, \theta_{A-x})$$

The first term is the measured three-body cross section, KF is a kinematical factor and ϕ stands for a momentum distribution of the spectator part of the cluster. The last term is then the two-body nuclear cross section without influence of Coulomb fields.

The THM has two other advantages. It allows to avoid uncertainties of extrapolation of S-factor that is used in direct approach and it lacks of the effect of electron screening, that increases with decreasing energies.

The THM was suggested by Baur [4] and was practically implied by group of C.Spitaleri from INFN LNS Catania. More details of the method can be found in ref. [5] and references therein.

3. Recent experiments

Recently, there were performed successful ANC and THM experiments using beams with a cluster structure ^{3}He and ^{2}H

ANC for the $^{14}C(n,gamma)^{15}C$ from $^{14}C(d,p)^{15}C$ reaction

The ^{14}C(n,gamma)^{15}C reaction is important in inhomogeneous big bang models, because it competes with other reactions on ^{14}C, that all lead to heavier nuclei. The ANC of this reaction was determined using mirror symmetry from a broad resonance in ^{15}F [6]. In the same work it was shown that this neutron radiative capture is a peripheral reaction. Different measurements were performed (see Table 2) and different approaches were used to extract the ANC value. Reanalysis of 35 years old data appeared not successful (not shown here). New measurement with FR-ADWA analysis with two sets of optical model potentials gave the results very well corresponding to other methods and moreover the accuracy was shown to increase.

Table 2. ANC's for g.s. ^{15}C(n,γ) determined by different methods in fm^{-1}

	mirror symmetry [6]	knockout data [7,8]	Coulomb dissociation [9]	^{15}C FR-ADWA [10]
$C^2_{0\,½}$	1.89 +- 0.11	1.48 +- 0.1	1.64 +- 0.03	1.64 +- 0.26

New astrophysical S factor for the $^{15}N(p,\gamma)^{16}O$

The reaction ^{15}N(p,γ)^{16}O is a reaction of a leak from the CN cycle to CNO II and CNO III cycles. A reaction ^{15}N(^{3}He,d)^{16}O was used to study this process that is dominated by two low lying resonances and direct capture to the ground state [11,12]. ANC's obtained from DWBA analysis together with R-matrix fit were used to obtain the S-factor S(0)=36.0+-6 keVb, which is about factor two lower than the previously accepted value. Due to this reaction, CN cycle looses 1 over 2200+-100 cycles, while the previously accepted value was 1200+-100 cycles. Later, the reaction was measured in LUNA collaboration and their value 39.6+-2.6 keVb was found [13].

THM for the 6Li(d,alpha)4He

A particle invariance was studied for the THM method with ^{6}Li(d,α)^{4}He and ^{7}Li(p,α)^{4}He reactions [14]. The ^{6}Li(^{3}He,αα)H and ^{7}Li(^{3}He,αα)^{2}H three-body reactions respectively were used to find an eventual instability of the THM results with respect to a choice of the different spectator particles.

The PWA approach was shown to be valid in both cases. Moreover, the choice of the cluster containing the projectile (i.e. choice of the spectator particle) does not change the THM results.

Low-energy d+d fusion reactions via the Trojan Horse Method

The ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions have been indirectly studied [15] by means of the Trojan Horse Method. The three-body reactions ^{2}H(^{3}He,p^{3}H)^{1}H and ^{2}H(^{3}He,n^{3}He)^{1}H were used to obtain data about the above two-body sub-processes. These d-d reactions have important implications for evolution of early universe and early solar system, as well as for the fusion energy applications. These reactions were studied in the energy range from 1.5 MeV down to 2 keV, where the data obtained were free of the election screening. The new S-factors were obtained for the two reaction channels ^{2}H(d,p)^{3}H S(0)=57.4 (1.8) MeVb and ^{2}H(d,n)^{3}He S(0)=60.1 (1.9) MeVb and they differ by about 15% from the previously accepted values.

Apart from light charged particles for astrophysical research, the U120M cyclotron also delivers charged particles for activation to probe reaction models with excitation functions and to obtain activation data. To name an example, production of ^{14}O in ^{3}He(^{12}C,n) reaction was studied in a frame of development of radioactive target in SPIRAL2 future facility [16].

Fast neutrons generators based on reactions of light particles on targets of Be, Li and D_2O, can deliver neutron fields to study activation of materials for IFMIF and similar facilities and radiation hardness tests [17].

4. Summary

An overview of the U120M cyclotron parameters and recent experiments with nuclear astrophysics aspects, that were performed using U120M light particle beams, was presented. The device proves to be very useful in the field of nuclear astrophysics when indirect methods, in our case ANC and THM are exploited.

5. Acknowledgments

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