International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 03 Mar. 2025, pp: 429-434 www.ijaem.net ISSN: 2395-5252

Using the delta isobar method in the study of resonances at the Nuclotron internal target

Igamkulov[1] Z.A., Dryablov[1] D.K., Sattarov[2] S.A.
[1] *Joint Institute for Nuclear Research, Moscow Region, Russian Federation, Dubna;*
[2] *Jizzakh Polytechnic Institute, Jizzakh, Uzbekistan.*

Date of Submission: 10-03-2025 Date of Acceptance: 20-03-2025

ABSTRACT: This article examines the two-step formation process of the Δ(1232) resonance using the Nuclotron's internal target. Kinematic calculations of the pion production cross-section in pA interactions are employed for reaction analysis. A practical method is proposed for determining the Δ(1232) resonance production cross-section on the Nuclotron's carbon-12 (^{12}C) target. This method allows estimation of the total Δ(1232) resonance formation cross-section based on estimating the energy of incident protons (p) and deuterons (d) striking the internal target. Calculations are also presented for the yield of $Y(\pi^- \ p)$ events resulting from the in-medium decay of the η-meson, based on the proposed method.

KEYWORDS: Nuclotron, internal target, pA reaction, delta isobar, production cross-section, pions, exotic nuclei.

I. INTRODUCTION

The investigation of exotic nuclei produced through the fusion of various mesons (η, ρ, ω, φ…) with a residual nucleus in πA, pA, dA, and other reactions remains a topic of significant contemporary interest. Experimental determination of the properties of η-meson nuclei – such as their binding energies and widths – alongside the testing of theoretical models concerning chiral symmetry in dense nuclear matter, and the study of the interaction mechanisms between η mesons and nuclear nucleons, is of considerable importance. These objectives drive the development of novel research methods and dedicated experimental setups.

In experiments on the study of η-meson nuclei, a two-arm spectrometer is usually used, located on both sides of the internal target station, perpendicular to the axis of the incident ion beam. The operating principle of such a spectrometer is based on measuring the speed and kinetic energy of a particle. The energy is determined by the time of flight (ΔT) and the absorbed energy (E-ΔE) in the detector material.The SCAN facility (JINR, High Energy Physics Laboratory) is designed to study the structure of exotic nuclei and investigate the properties of the bound state of various mesons and nucleon resonances in the nuclear environment [1].

It is distinguished by high efficiency of registration of protons and charged pions from the decay of $S_{11}(1535)$ resonance, in the momentum range for pions ~ 90% and ~ 95% for protons. The geometric acceptance of each of the arms of the SCAN facility is $\theta = 60$ and $\phi = 350$. The resolution of the TOF system is ~ 150 ps. Identification of the bound meson-nucleus state is carried out by the decay of the generated resonance, which arises as a result of the fusion of the meson and the nuclear residue. For example, in the "η-meson – nucleus" coupling, the correlated components of the (πN)-pair from the decay of the nearly stationary $S_{11}(1535)$ nucleon resonance are registered (in energy and expansion angle ~180^0). Since the decay of the $S_{11}(1535)$ resonance (with equal probability ~50%) occurs both on the πN and on the ηN pair, a sequence of $\eta N \rightarrow S_{11}(1535) \rightarrow \eta N\ldots$ transitions arises in the η-meson nucleus.

This sequence can break up into a (π + N)-pair, the kinetic energies of which are sufficient to escape from the nucleus. Its decay into a (π + N) pair occurs at an angle of ~180^0, since the impulse of the $S_{11}(1535)$ resonance formed near the birth threshold is almost equal to zero. In the experiment to search for η-meson nuclei [2], the following reaction was used in the internal beam of the Nuclotron:

$$p+A \rightarrow (A-1)\eta+n+p$$

$$\eta+N \rightarrow S_{11}(1535) \rightarrow \eta+N \rightarrow \ldots \rightarrow S_{11}(1535) \rightarrow \pi+N$$

For such (π and N) pairs, a correlation arises both in the angle of expansion $<\Theta_{\pi N}>$ and in the energies of the components of the (π and N) pair.

Since the minor impulse of the $S_{11}(1535)$ resonance is oriented randomly and the scattering angle is $<\Theta_{\pi N}> \approx 180^0$, then the particle energy will be distributed as $<E_\pi> \approx 300$ MeV, $<E_N> \approx 100$ MeV. It is these events that were recorded in the experiment [2], where the decay of the $S_{11}(1535)$ resonance into a correlated (π-p) pair was studied.

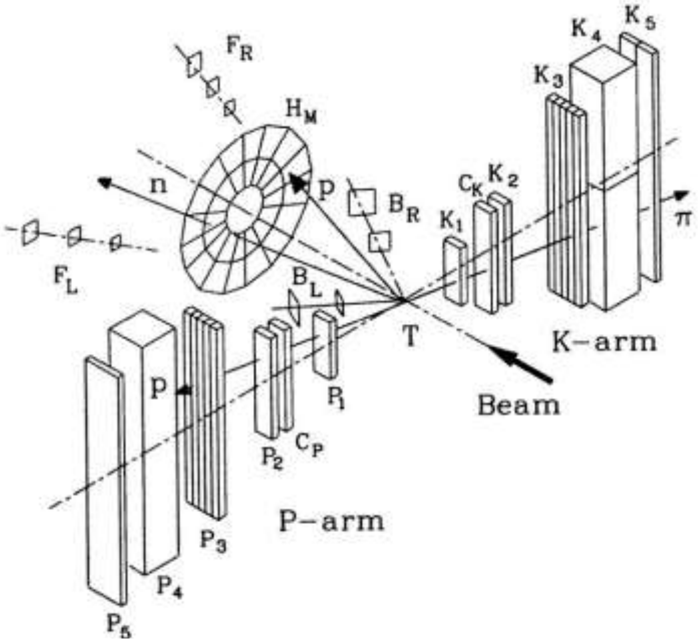


Fig 1. The SCAN facility for searching and studying exotic nuclei on the internal target of the LHEP Nuclotron, consisting of two arms (P- and K-arms)

However, precise measurement of the yield of precisely such pairs is difficult due to the smallness of the total cross section for the formation of η-nuclei. In addition, the simulation results and experimental data differ significantly.

This problem can be solved by considering another reaction with a similar final decay product. For example, the formation of a resting Δ(1232)-isobar in the nucleus of the residue after the pA interaction, since one of the mechanisms of the process of formation of the Δ(1232)-isobar in the target nucleus similarly repeats almost all stages of the formation of the η-meson nucleus. The only difference is that the cross section for the production of the Δ(1232) isobar in the pA reaction is of the order of tens of mb, while the total cross section for the production of η nuclei in the same reaction is only a few μb.

Thus, the delta isobar could be used as a defining points in measurements to find η nuclei.

II.THE DELTA ISOBAR METHOD IN THE STUDY OF RESONANCE DECAY

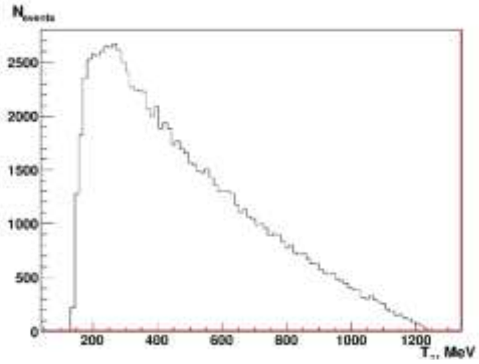
To calculate the 4-impulse of π-mesons produced in proton-nucleus collisions, the Gen Bod simulation program [3] was used. Based on the obtained data, the distribution of pions $N_{part}(T\pi)$ is constructed depending on the kinetic energy, which is then normalized to the total number of events (Fig. 2).

The problem of determining the probability of π-meson production in a pA reaction can be solved from known data on πA scattering. For example, Figure 3 shows the total cross section of $\pi^{12}C$ scattering as a function of the kinetic energy of pions (data from ([4-6]).If we multiply these two distributions (Fig. 2 and Fig. 3) in the same interval of pion kinetic energy ($0 \leq T\pi \leq 320$ MeV) we get a histogram $[\sigma(T\pi)*N_{self}(T_\pi)]$ (see Fig. 4). We obtain the value of the cross section for the formation of Δ-resonance in inelastic p-A collisions by integrating the histogram (Fig. 4) over the kinetic energy of pions Tπ. In this calculation model, a nearly quiescent Δ- resonance is formed by the capture of a secondary π-meson produced in the pA reaction by the target nucleus.

The cross sections of produced π-mesons in inelastic $p^{12}C$ collisions are as follows: $\sigma_\pi = 66.56$

mb; 62.87 mb; 53.12 mb and 47.10 mb, respectively, for the working energies at the internal target of the Nuclotron: Tp = 1.4 GeV; 1.5 GeV; 1.7 GeV and 1.9 GeV.

For these proton energies, the data from [7-9] show that with a cross section value of $\sigma_{in} \approx 248$ mb for inelastic $p^{12}C$ interaction, the fraction of the cross section with pion production is $\sigma_\pi = 49$ mb.



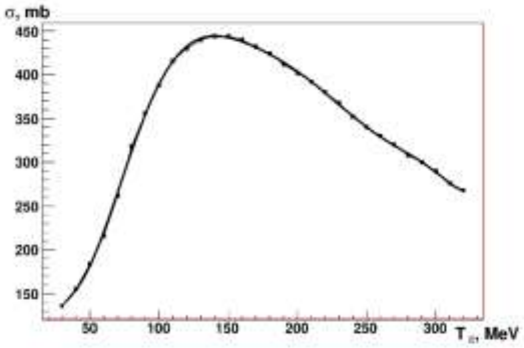


Fig. 2. Distribution of pions from the kinetic energy produced as a result of an inelastic $p^{12}C$collision. Fig.3. Total cross-section of $\pi^{12}C$ scattering depending on the kinetic energy of pions.

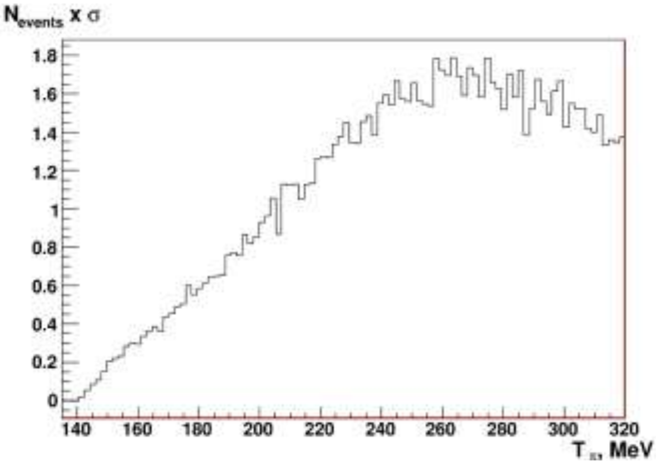


Fig.4. $\sigma_\pi \times$ Nevents - multiplied histogram (Fig. 2 and 3) from the kinetic energy of pions T_π

We obtain the cross section of the production of delta resonance for the specified proton energies taking into account the value of the ratio (σ_π/σ_{in}):

Interaction energy, GeV	T_1=1.4	T_2=1.5	T_3=1.7	T_4=1.9
Birth cross section, mb	σ_1=13.	σ_2=12.42	σ_3=10.80	σ_4=9.86

The delta resonance decays with a high probability of ≈ 0.99 into a pion-proton pair. The products can be registered under experimental conditions, since the Δ-resonance and the pion-nucleon pair fly apart relative to each other at an angle of about $\sim 180^0$ (in a 4π solid angle).

We used the Breit-Wigner formula to describe the Δ- resonance and modeled the protons and pions from the decay of this resonance. These pions will then be recorded by the SCAN facility. Protons with impulse greater than ≥ 240 MeV/c (Fig. 5, c- speed of light in vacuum) were registered using the GEANT program (taking into account the resolution of the two-arm SCAN spectrometer). The pair produced during the decay of a resting Δ-resonance (π-p) has a low impulse due to ionization energy losses. In most cases, protons stop in the substance (scintillator) of the recording detectors of the SCAN facility, and at the same time, slow π-mesons also decay in the same interval. Monte Carlo calculations show that the SCAN facility registers only 1/10 of the delta resonance decay products [10] (10% of the total number of particles falling within the angular acceptance of the detectors, see Fig. 5).

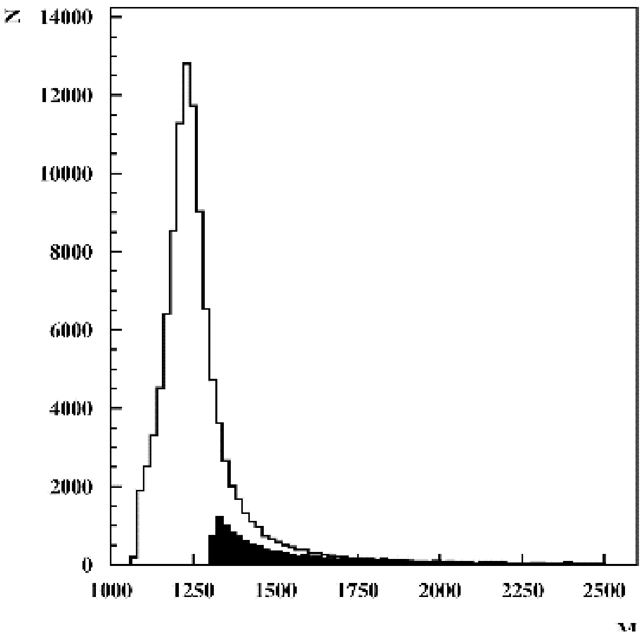


Fig. 5. Graph of the distribution of the effective mass of two particles from the decay of Δ-resonance, constructed using the Monte Carlo method using the Breit-Wigner formula.

Taking into account the above factors, for the above energies of the incident proton beam, the effective cross-sections of secondary protons have the following values: σ_1= 1.315 mb (1.4 ГэВ);σ_2= 1.242 mb (1.5 ГэВ);σ_3=1.08 mb (1.7 ГэВ);σ_4= 0.986 mb (1.9 ГэВ).

The obtained data provide an estimate of the expected yields of Y(pπ-) events with the formation of delta resonance during experiments on the internal beam of the Nuclotron [11]:

$$Y(p,\pi)=\sigma(p^{12}C\to \to N_1N_2\cdot (A-1)_\Delta)N_t\cdot\ N_{eff}\cdot\ Br(\pi N)\xi\cdot\ \Omega_\pi\cdot\ n_c\cdot\ k\cdot\ f(\Omega_p/\Omega_\pi)g \quad (1)$$

$N_t=0.85\cdot10^{20}$ nuclei/sm^2 - the number of ^{12}C nuclei in 10 μm of carbon target filament;

N_{eff} = 3.0·1015 – effective flux of protons falling on the target during a cycle time of 5 s;

Ω_π= 8·10-3 sterad. - solid angle of particle registration of the SCAN setup;

Br(πN) = 0.99 - probability of decay of Δ in πN channels;

ξ(π-p) = 0.50 - probability of decay of Δ into a (π-,p) pair;

$f(\Omega_p/\Omega_\pi)\approx 0.2$ is the correlation geometric function of πp-decay, determined by the “blurring” of the particle expansion angle due to the Fermi motion of nucleons;

n_c = 360 – number of acceleration cycles of charged particles of the Nuclotron in 1 hour;

k = 3.3·10-3 – ratio of transverse dimensions of the p-beam and target;

g – fraction of the Gaussian beam hitting the thread target = 0.5;

Using these numerical values for the factors in (1), we obtain:

Tp=1.4 GeV Y(pπ-) ≈ 158,000 events/hour
Tp=1.5 GeV Y(pπ-) ≈ 149,000 events/hour
Tp=1.7 GeV Y(pπ-) ≈ 130,000 events/hour
Tp=1.9 GeV Y(pπ-) ≈ 118,000 events/hour

For the Nuclotron deuteron beam, these yields are expected to be twice as high.

III. ESTIMATION OF THE EVENT YIELD FOR THE DECAY OF ETA-MESON NUCLEI

The same event yields $Y(\pi^-p)$ in the reaction of formation of η-nuclei in pA-collisions, for the carbon target ^{12}C can be written as in formula (1):

$Y(\pi^- p) = \sigma\eta\,(N\,^{12}C \rightarrow (\eta(A-1)X)\,N_t\,N_{eff}\,Br(\pi N)\,\xi\Omega_\pi\,n_c\,k\,f(\Omega_p / \Omega_\pi)\,g$ (2)

here $\sigma\eta(N^{12}C\rightarrow\eta(A-1)X)$is the total cross section for the production of η-nuclei in the pA reaction, which is taken to be equal to 5% of the cross section for the production of η-mesons in $((pp \rightarrow pp\eta) + (pn \rightarrow pn\eta) + (pn \rightarrow dn\eta))$ collisions (by analogy with the cross section for the photoproduction of η-nuclei).

Taking into account the above considerations, for the total cross section σ_η of η-nucleus production in the $p^{12}C$ reaction we obtain the following value:

$\sigma\eta(p^{12}C\rightarrow_\eta(A-1)X)=[6\ \sigma(pp(n) \rightarrow\eta\ p(n)p) \times F(11B)] \times 0.05 = 6 \times 110 \times 10\text{-}30 \times 0.1 \times 0.05 = 3.3 \times 10\text{-}30\ \text{sм}^2 = 3.3 \times 10^{-6}\text{barn} = 3.3\ \mu b$ (3)

here $F(^{11}B)$ is the form factor of the ^{11}B core, taken equal to 0.1. When determining the total cross section for the production of η-mesons in pA collisions, the sum of the values of the experimental cross sections of elementary processes was used [12] (see Fig. 6):

$\sigma t\ (p\ p \rightarrow p\ p\ \eta) = 5\ \mu b$

$\sigma t\ (p\ n \rightarrow p\ n\ \eta) = 35\ \mu b$

$\sigma t\ (p\ n \rightarrow d\ \eta) = 70\ \mu b$

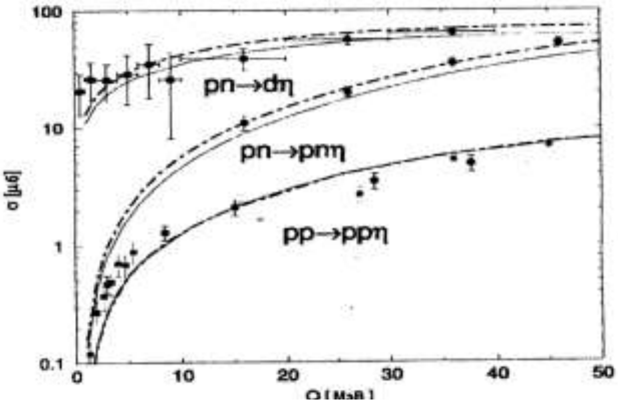


Fig. 6. Total cross sections of reactions pp→ppη, pn→pnη and pn→dη [12].

A Thus, when calculating the expected yield of events - (π-p) of a pair of particles from the decay of $S_{11}(1535)$ in the pA reaction, we use the following values:

the number of ^{12}C nuclei in 10 μm of the target-filament is: $N_t = 0.85\cdot10^{20}$ nuclei/sm^2;

the flux of protons N_{eff} falling on the target per cycle: $N_{eff} = 3\cdot10^{15}$ /cycle (for 5 sec);

solid angle Ω_π of the spectrometer: $\Omega_\pi = S/(4\pi R^2) = 8\cdot10^{-3}$ sterads;

$Br(\pi N) = 0.5$ (the probability of decay of $S_{11}(1535)$ in πN and ηN channels is approximately the same);

$\xi(\pi\text{-}p)= 0.33$ - the probability of decay of $S_{11}(1535)$ into a (π-p) pair;

$f(\Omega p\ /\ \Omega\pi) \approx 0.2$ is the correlation geometric function of π-p-decay, determined by the “blurring” of the angular divergence of particles due to Fermi motion.

Using all the given numerical values of the factors in relation (2), for the expected yield of (π-p) pairs from the decay of the $S_{11}(1535)$ resonance in the target nucleus for p12C collisions ($Ep \approx 2$ GeV/nucleon) we obtain: $Y(\pi^- p) \approx 133$ events/hour.

IV. CONCLUSION

It has thus been shown that by measuring the masses of mesons and their interactions with nuclei, new information can be obtained in the detailed understanding of dynamical symmetry breaking in low-energy quantum chromodynamics (QCD). The data from experiments at the SCAN (LHEP) facility help to study the properties of bound η-meson states. In particular, measuring the parameters of resonance decay products (for example, (π-p)-pairs) allows us to study the conditions for the birth of the $S_{11}(1535)$-resonance on the internal target of the Nuclotron in pA- and dA-reactions. The small recoil of the reaction, the small momentum received by the target nucleus, allows the decay products (π-p-pair) to fly out of the nucleus at an angle of $\approx180^0$ relative to each other. Registration of paired particles flying out at such angles is the main idea for isolating the decay of η-meson nuclei.

REFERENCES

[1]. Afanasyev S.V., Bazylev S.N. etc. Collection system data and installation

trigger SCAN // -IET. -2008.-No. 1. -P.34-39.

[2]. Anikina M.X. , Afanasyev S.V. etc. Research program in physics η –meson nuclei at the Nuclotron LHE JINR // Preprint FIAN.-Moscow. 2003.- No.21.3.

[3]. James F. W515 N-Body Monte-Carlo Event Generator//Monte Carlo Phase Space.- CERN 68-15.-1968.

[4]. Barashenkov V.S. Cross-section of interaction of particles and nuclei with nuclei// - Dubna.-JINR.-1993 (346 p).

[5]. Binon F., Dutel P., Garron J.P. et. al. Scattering of Negative Pions on Carbon // Nuclear Physics.B.-1981.-V.17, No.1.-P.168-188 (Amsterdam).

[6]. Strokovsky E.A., Gareev F.A., Ratis Yu.L. Delta isobaric excitation of atomic nuclei in charge-exchange reactions // ECHAYA.- 1993.- T. 24.-Issue 3. -C.603-682.

[7]. Cugnon J., Mizutiani T., Vandermelen J. Equlibration in Relativistic Nuclear Collisions. A Monte Carlo Calculation // Nuclear Physics.A.-1981.-V.352, No.3. -P. 503-534 (Amsterdam).

[8]. VerWest B.J., Arndt R.A. NN Single Pion Production Cross Section Below 1500 MeV // Phys. Rev.C.-1982.-V.25, No.4.-P.1979-1985.

[9]. Nagamiya S., Lemaire M.C., Moeller E. et.al. Production of pions and light fragments at large angles in high-energy nuclear collisions // Phys.Rev.C.-1981.-V.24, No.3.-P.971-1009.

[10]. Igamkulov Z.A., Afanasyev S.V., Bekmirzaev R. et al. Estimation of the cross section of Δ-resonance production in pA-collisions for the internal target of the Nuclotron // Letters to ECHAYA.-2010.-Vol.7.-№2 (158).-P.200-208.

[11]. Litvinenko A.G., Stavinsky V.S. Upper limit of cross sections for production of cumulative isobars, π-mesons from analysis of deformations of inclusive spectra. - JINR Brief Communications.-1985.-№12.

[12]. Baru V., Gasparyan A. M., Haidenbauer J. et al. Production of η-mesons in nucleon-nucleon collisions // Physical Review C.-2002.-V.67.-P. 024002.