STUDY OF EXOTIC WEAKLY BOUND NUCLEI USING MAGNETIC ANALYZER MAVR

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Abstract. A project of the high-resolution magnetic analyzer MAVR is proposed. The analyzer will comprise new magnetic optical and detecting systems for separation and identification of reaction products in a wide range of masses (5–150) and charges (1–60). The magnetic optical system consists of the MSP–144 magnet and a doublet of quadrupole lenses. This will allow the solid angle of the spectrometer to be increased by an order of magnitude up to 30 msr. The magnetic analyzer will have a high momentum resolution ($10^{-4}$) and high focal-plane dispersion (1.9 m). It will allow products of nuclear reactions at energies up to 30 MeV/nucleon to be detected with the charge resolution ~1/60. Implementation of the project is divided into two stages: conversion of the magnetic analyzer proper and construction of the nuclear reaction products identification system. The MULTI detecting system is being developed for the MAVR magnetic analyzer to allow detection of nuclear reaction products and their identification by charge $Q$, atomic number $Z$, and mass $A$ with a high absolute accuracy. The identification will be performed by measuring the energy loss ($\Delta E$), time of flight (TOF), and total kinetic energy (TKE) of reaction products. The particle trajectories in the analyzer will also be determined using the drift chamber developed jointly with GANIL. The MAVR analyzer will operate in both primary beams of heavy ions and beams of radioactive nuclei produced by the U400 - U400M acceleration complex. It will also be used for measuring energy spectra of nuclear reaction products and as an energy monochromator.

1. Introduction

One of the scientific research fields at the Flerov Laboratory of Nuclear Reactions (FLNR), JINR, is studying the mechanism of nuclear reactions in beams of accelerated stable and radioactive nuclei. Another research direction is the study of properties of nuclei near the nucleon drip line. Experiments are carried out at the U400 and U400M cyclotrons of FLNR and in cooperation with the research centers GANIL (France), RIKEN (Japan), and Cyclotron Laboratory (Juväskylä, Finland). The experimental procedure involves magnetic spectrometers and separators that provide high purity separation of reaction products from the primary beam and high resolution in momentum and accordingly in energy and mass.

At FLNR the stability and structure of very neutron-rich nuclei of the lightest elements (\textsuperscript{7,10}$^\text{He}$, \textsuperscript{9,11}$^\text{Li}$, \textsuperscript{12,14}$^\text{Be}$) were investigated using the MSP–144 magnetic analyzer, the structure of heavy isotopes of these nuclei was investigated using the missing mass method, and their binding energy and stability
were determined. The data on the energy levels in the nuclei $^7$He, $^8$He, $^{10,11}$Li, and $^{13}$Be were obtained for the first time. The experiments were simultaneously conducted in Dubna and Berlin using intense beams of $^{11}$B, $^{13}$C, and $^{14}$C heavy ions and the MSP–144 and Q3D precision magnetic spectrometers [1, 2]. In one of the U400 channels a beam energy monochromatization system was installed. In combination with the MSP–144 magnetic analyzer it allowed producing beams with a high energy resolution (no worse than 250 keV). When it became possible to obtain relatively intense beams of radioactive nuclei at the U400M cyclotron of FLNR JINR, a system was developed for separating nuclear reaction products resulting from fragmentation of the 50-MeV/nucleon primary beam on the production target (QD spectrometer). This magnetic system allowed secondary beams of $^3$He and $^6$Li nuclei with an intensity of $10^4$ s$^{-1}$ to be produced and then used in the first experiments for measuring angular distributions of the $^4$He and $^6$Li ions elastically scattered from various target nuclei. Data on interaction radii of these nuclei were obtained for the first time [3, 4]. Later experiments on measurement of excitation functions for complete fusion reactions with subsequent evaporation of neutrons and fission in a wide energy range (10–70 MeV) were carried out with $^4$He beams of the DRIBs acceleration complex using the MSP–144 spectrometer. These experiments were the first to yield results indicating to a possibility of deep sub-barrier fusion of $^4$He (neutron halo nucleus) with other heavy nuclei [5, 6]. These results stimulated further experimental and theoretical investigations of sub-barrier reactions with loosely bound nuclei in many research centers and are still a topic for discussion at practically all international conferences on physics of exotic nuclei. A series of experiments was carried out at the QD spectrometer to study energy dependences of total reaction cross sections for interaction of $^4$He, $^6$He, $^6$Li, and $^9$Li nuclei with Si nuclei [7]. A unique procedure based on the use of an active Si target, which is a multilayer semiconductor telescope of thin Si detectors, allowed one-by-one detection and identification of nuclear reaction products and determination of their total interaction cross section as a function of energy. It was an important step toward understanding the mechanism for interaction of loosely bound nuclei in a wide energy range. Startup of the new DRIBs complex for acceleration of radioactive beams opened up new possibilities for those investigations [8]. Reactions with $^4$H nuclei near the Coulomb barrier energy were further investigated at a new experimental level (relatively high intensity of radioactive beams, good momentum resolution of the MSP–144. The intensity of the $^4$He beam on the physical target was $3–5 \times 10^7$ s$^{-1}$, which allowed the previous experimental sensitivity to be improved by several orders of magnitude. In addition, monochromatization of the secondary beam energy by the magnetic spectrometer made it possible to measure excitation functions for fusion and neutron transfer reactions with $^4$He nuclei with an accuracy no worse than 300 keV. The supporting evidence was obtained for the earlier observed enhancement of the cross section for complete fusion of $^4$He nuclei in the sub-barrier energy region [9]. Measurements of the cross section for fusion with $^4$He nuclei with the formation of the same compound nucleus as in the case of fusion with the $^6$He nucleus revealed a great difference between the interaction mechanisms of these two neighboring nuclei. Interesting results were obtained for transfer reactions involving loosely bound nuclei (single- and two-neutron transfers from the $^4$He nucleus [10] and deuteron transfer from the $^6$Li nucleus [11]). In both cases the maxima of the transfer reaction cross sections corresponded to the energy equal to the Coulomb interaction barrier and were as high as one barn. These results are of great interest to nuclear physics and astrophysics. It is worth mentioning that all those experiments were conducted in close collaboration with physicists from the JINR Member States: NPI ASCR (Rez, Czech Republic), IFIN–HH (Bucharest, Romania), NINP PAS (Krakow, Poland), and others.

2. Proposed MAVR technical characteristics
The investigations described above require high Z and A selectivity of reaction products, a large solid angle of reaction product detection, a high energy resolution, and a high purification factor in separation from the primary beam. In addition, it is necessary to segregate events from the background, which is $10^{10}$ to $10^{12}$ times higher, with an energy resolution of up to $10^{-3}$, i.e., it is needed to combine the high energy resolution with a high degree of purification from the primary
beam. The momentum resolving power $\Delta p/p \sim 10^{-4}$ obtained by magnetic analysis allows one to have the energy resolution about 100 to 200 keV for the bombarding particles like $^{12}$C, $^{16}$O, $^{20}$Ne at energies up to 30 MeV/A. In view of this, the experimental setup should meet the following requirements:

1. The solid angle of the setup should be no smaller than 30 msr to allow carrying out highly efficient correlation experiments.
2. It should be possible to detect nuclear reaction products, including neutrons, in a wide range of angles, among them the angle $\Theta_{lab} = 0^\circ$.
3. It should be possible to compensate for the kinematical spread of nuclear reaction products at a large solid angle.

Various detector techniques in combination with a high-resolution magnetic analyzer MAVR are supposed to be used for ensuring better efficiency of heavy ion beams and beams of radioactive nuclei from the DRIBs acceleration complex. The proposed magnetic analyzer will have a large solid angle for detection of reaction products (up to 30 msr), a high momentum resolution ($10^{-4}$), and a high dispersion in the focal plane (1.9 m). This analyzer will allow products of nuclear reactions at energies up to 30 MeV/nucleon to be detected with a high charge resolution ($\sim 1/60$), which is especially important for separation of heavy nuclear-reaction products. It is planned to construct the analyzer in two stages.

At the first stage the analyzer will be equipped with a special beam collimation system, instrument transducers for precision measurement of the magnetic field (NMR teslameter), profilometers based on multiwire proportional chambers, and a time-of-flight measurement system. A new detector module based on drift chambers and VME electronics will be made and tested.

At the second stage the MAVR analyzer will be mounted in the new U400R hall. The layout of the spectrometer in the U400R experimental hall, now under construction, is shown in Fig. 3. The MAVR construction is supposed to involve the following activities.

2.1. Development of the magnetic optical system for the MAVR analyzer

The MSP–144 magnetic spectrometer is intended for analyzing and detecting products of nuclear reactions in beams of accelerated ions with the maximum magnetic rigidity up to 1.45 Tm. This broad-range stepped-poles magnetic spectrometer was developed for analysis of light products of nuclear reactions with protons. High ion-optical parameters of the spectrometer allow its electromagnet to be used for analyzing heavy nuclear-reaction products with masses $A = 40–100$. The magnet consists of two regions. The magnetic field in the first region is 1.46 to 1.5 times lower than in the second region. This magnet is characterized by a wide energy range of detected reaction products ($E_{min}/E_{max} = 5.2$), high dispersion-to-enlargement ratio $D_d/M_x \sim 6.3$ m, and relatively large solid angle $\Omega$ up to 5 msr. It has a high resolving power $R_a = 2000$ and a high dispersion $D_a = 1.9$ m. This spectrometer is second to those currently available in other research centers only in the solid angle.

2.2. Increasing the solid angle of the magnetic analyzer

The solid angle of the reaction product capture can be increased to 30 msr by installing two quadrupole lenses and moving the target from its current position as far as $S = 1.7$ m. For this purpose it is necessary to manufacture two quadrupole lenses with magnetic field gradients $-1018$ Gs/cm and $+895$ Gs/cm. A doublet of quadrupoles in front of the analyzer will decrease the distance $S$ between the entrance to the magnet and the new position of the target as compared with a single quadrupole [12] and increase the horizontal acceptance of the analyzer by a factor of 3. The vertical size for reaction product capture in front of the entrance to the analyzer will decrease to the size of its vertical aperture, and the vertical acceptance of the separator $y_0$ will increase by a factor 6. The dispersion in the focal plane of the analyzer will practically stay unchanged whereas the resolving power will decrease by about a factor of 3.

The calculations [12] show that the most effective way to increase the solid angle of the existing spectrometer is to use a doublet of quadrupoles. Given the calculated geometry of the quadrupoles and the field gradients $G_1 = -1018$ Gs/cm and $G_2 = +895$ Gs/cm, the product of the angular acceptances of
the separator (solid angle) will be about 30 msr. This in turn will require manufacturing a new receiving chamber for the focal detector in view of a change in the position of the focal plane.

Table 1. Characteristics of magnetic analyzers

|       | D (cm/%) | Δp/p (%) | Br (Tm) | dΩ (msr) | Energy resolution dE/E | TOF resolution dT |
|-------|----------|----------|---------|----------|------------------------|------------------|
| MAVR  | 1.9      | 10       | 1.5     | 30       | 5*10^-4                | -                |
| VAMOS | 2.5      | 10       | 2.3     | 80       | 5*10^-3                | -                |
| SPEG  | 7        | 7        | 3.2     | 4.9      | 5*10^-3                | -                |
| PRISMA| 4.0      | 10       | ~2.0    | 80       | 1*10^-3                | -                |
| Q3D(HMI)| 9.5    | 10       | 1.7     | 10       | 2*10^-4                | <1 ns            |

Table 1 presents the expected characteristics of the MAVR analyzer in comparison with the spectrometers in other research centers.

2.3. Detecting system

The MAVR magnetic analyzer is supposed to accommodate a specially developed MULTI detecting system capable of detecting and identifying nuclear reaction products by charge Q, atomic number Z, and mass A with a high absolute accuracy.

Figure 1 shows a model of the MAVR magnetic analyzer with a new reaction chamber and a doublet of lenses. The MAVR can rotate through an angle up to 112° relative to the beam axis.

![Figure 1. General view of the MAVR high-resolution magnetic analyzer.](image)

Nuclear reaction products will be identified by A, Z, and Q through measurement of the energy loss (ΔE), time of flight (T), and total energy (E) of particles, i.e., the dependences ΔE-E and ΔE-T (or E-T), which requires reproduction of the particle motion trajectory in the analyzer. This will be done using the drift chamber developed together with the VAMOS group (GANIL).

The drift chamber to be used for measuring the particle energy loss (ΔE) and total energy (E) is schematically shown in Fig. 2. The time of flight will be measured using the parallel-plate-avalanche detector (PPAC).

Correlated reaction products arriving at the focal detector can be detected by position-sensitive semiconductor telescopes and also by a multiwire proportional chamber [13]. Since the range of problems to be solved by the proposed setup is rather wide, the focal detector will be made as a set of individual compatible modules.
3. Expected period of construction and estimated cost of work
It is planned to construct the MAVR setup in 4 years. Preparatory work and manufacture of individual units will be carried out independently of the construction of the extension to the U400R accelerator hall.

The estimated cost of the work to design and manufacture MAVR setup units and to mount and test the MAVR setup is about $750,000.

4. Collaborating organizations
INRNE, BRV, BAS (Sofia, Bulgaria), NPI, AS, CR (Rez, Czech Republic)
INP, PAS (Krakow, Poland)
GANIL (Caen, France), IPN (Orsay, France)
NRC Kurchatov Institute (Moscow, Russia)
AANL (Yerevan Phys. Inst., Yerevan, Armenia)
JYFL (Cyclotron Laboratory, University of Yuvaskyla, Finland)
IP VAST (Institute of Physics, Vietnam Academy of Science and Technology, Hanoi)

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