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MONITOR REACTIONS IN Al-FOILS FOR HIGH ENERGY PROTON BEAMS BOMBARDING A THICK TARGET

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INTRODUCTION

Foil activation is a well-known technique for measuring the fluence of high energy proton beams[1,2,3]. Particularly, the reaction $^{27}Al(p, 3pn)^{24}Na$ is very convenient to measure the proton fluence in irradiations of thin targets at high energies. ^{24}Na has a suitable half-life of 14.96 hours and a gamma-line of 1368.5 keV. It is more convenient for us than other monitor reactions: ^{22}Na and ^{7}Be have too long half-lives (2.603 years and 53.3 days, respectively), they must be measured for long times as one needs large counting rates in order to obtain the statistical significance. ^{11}C has a too short half-life (20.38 min.).

In previous transmutation experiments, when bombarding Al-monitor foils in contact with thick targets (ϕ8cm×L21 cm) with 3.7 GeV protons, one observed an apparent fluence of protons considerably larger than given by the accelerator operators[4]. Therefore, we used the results from the monitor reaction $^{nat.}Cu(p, x)^{24}Na$ for proton fluence determination in this experiment. The Cu-plate (1 mm thick) had been placed in contact with the thick target. The proton fluence obtained this way agreed well with the one given by the machine operators[4]. It is well-known, that the reaction $^{nat.}Cu(p, x)^{24}Na$ is a typical high-energy reaction with appreciable cross section only above the threshold of approximately 0.8 GeV. Its excitation function is shown in Fig.1 (taken from Ref.[5,6]). On the other hand, it is well-known, that the reaction $^{27}Al(n, \alpha)^{24}Na$ has appreciable cross sections (94 mb) for neutrons with energies exceeding approximately 10 MeV[7]. Such high-energy neutrons are produced quite abundantly in thick targets by high energy protons. They are generated or scattered backwards in respect to the proton beam direction and they also produce ^{24}Na in Al monitor foils. It was shown experimentally, that the monitor reaction $^{27}Al(p, 3pn)^{24}Na$ provides correct results, provided the total target thickness is < 1 g / cm^2 for 24 GeV protons (Ref.[3]).

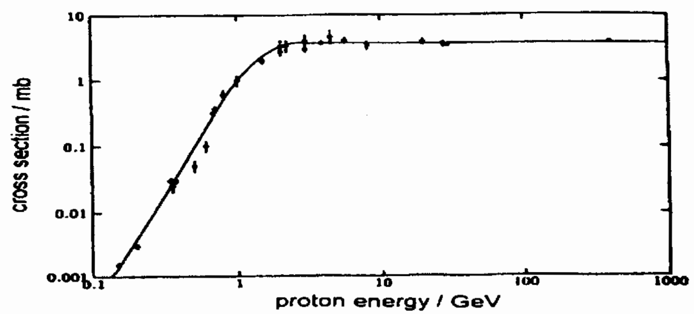

Fig.1: Excitation function for reaction $^{nat.}Cu(p, X)^{24}Na$[5,6]

It is the purpose of the communication to suggest a new monitor foil system for thick target systems exposed to high energy proton fluences. Such thick target systems are used in accelerator-driven-transmutation (ADT) experiments[4,5,8]. The experiments were carried out at the Laboratory of High Energies, Joint Institute for Nuclear Research (JINR), Dubna, Russia.

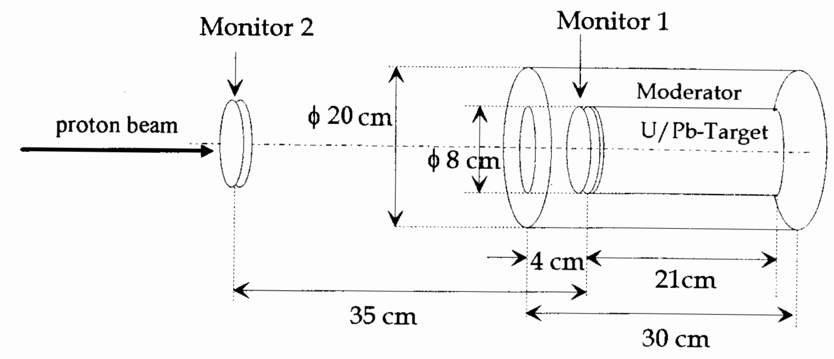

Fig 2.1: Uranium target set-up (with paraffin moderator)

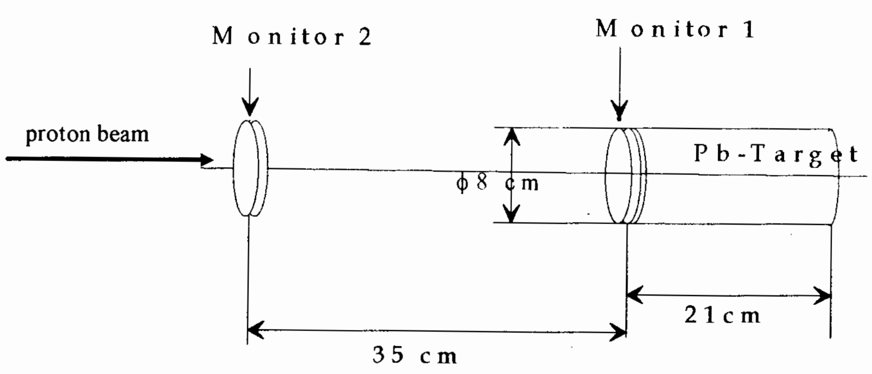

Fig.2.2 Lead target set-up (without paraffin moderator)

EXPERIMENTAL

Thick targets and monitor foils were irradiated for about one hour with a well-focused beam of 1.0 GeV and 1.5 GeV protons from Synchrophastron (JINR ,Dubna, Russia). The uranium target shown in Fig.2.1 consists of two blocks of ϕ3.6 cm $\times$L10.5 cm natural uranium covered with 2.2 cm thick lead, the lead mantel is then surrounded by a 6 cm thick paraffin moderator. A pure lead target is shown in Fig.2.2: a block of 20 cm Pb, composed of 20 disks (i.e. without the moderator), each ϕ8 cm $\times$L 1 cm. For each experiment two sets of monitors were utilized: monitor 1 and monitor 2. Each set of monitor is composed of 3 Al-foils (diameter 8 cm and 10 μm thick) plus one Cu-plate (diameter 8 cm and 1 mm thick). The monitor 1 was placed directly upstream in contact with the thick target; the monitor 2 was placed upstream 35 cm away from the target. It is well known that the fluence of a point radiation source at a distance of R is proportional to $1/R^2$. The distance of 35 cm is considered to be enough to prevent the influence of secondary particles produced in the target on the monitor foils, as will be shown in detail later. The irradiations were stopped after a proton fluence reached approximately 10^{13}. Afterwards, the monitor foils were measured for their gamma activities using a Ge(Li)-detector. For the gamma-spectrum analysis the GAMMAW[9] program was used. the gamma-line 1368.5 keV of ^{24}Na was employed. The cross sections of the reaction ^{27}Al(p, 3pn)^{24}Na are 10.5 and 10.0 mb for 1.0 GeV and 1.5 GeV protons, respectively[1,2], for reaction $^{nat.}$Cu(p, X)^{24}Na: 1.0 and 1.90 mb, respectively[6].

RESULTS AND DISCUSSION

The experimentally determined fluences of proton beam in this work are presented in Tab.1. As comparison, the fluences given by accelerator operators are also listed in this table. The fluences obtained with Al-monitor 1 are much larger than those obtained with Al-monitor 2. Al-monitor 2 gives about the same fluence as the Cu-monitor 1 and Cu-monitor 2. This shows experimentally, that the monitor 2 in a distance 35 cm upstream gives internally consistent results for the proton fluence. It is obvious, that the two fluences measured with both the Cu-monitor 1 and 2 agree within the statistical error because of their high threshold for the reactions $^{nat.}$Cu(n, X)^{24}Na. The radiochemically measured fluences agree at 1.5 GeV proton energy with those given by the accelerator operators with a deviation between 6% and 16%; at 1 GeV proton energy there is a larger discrepancy, the reasons are not known.

The errors given in Tab.1 consist of two parts: one is the statistical error, the other is the systematic error introduced by the cross section used. The cross section error for reaction $^{27}Al(p, 3pn)^{24}Na$ is 6.5%[1], however, there are no cross section errors given for reaction $^{nat.}Cu(p, x)^{24}Na$ in Ref.[5,6], but from the excitation function Fig.1 it is obvious, that the cross section errors must be relatively large at the proton energies of 1.0 GeV and 1.5 GeV, thus a error of 10 % was assumed in this work.

Tab.1: Fluence of proton beams bombarding U and Pb targets, in units of (E+13) particles and determined with Cu-and Al-monitors.

	measured Fluence (Cu-Monitor)		measured Fluence (Al-Monitor)		given Fluence (accelerator people)
Experiment	Monitor1	Monitor 2	Monitor1	Monitor 2*	
1.0 GeV p + U	1.22±0.14	1.09±0.13	3.15±0.24	1.23±0.09	2.00
1.5 GeV p + U	1.41±0.17	1.37±0.17	6.67±0.49	1.41±0.11	1.50
1.0 GeV p+Pb	1.22±0.14	1.25±0.15	2.19±0.17	1.30±0.11	2.04
1.5 GeV p+Pb	no measure	1.31±0.16	2.57±0.18	1.29±0.09	1.51

*: These fluences are considered to be the most reliable. They have the smallest uncertainty and will be used in further ADT studies (to be published later). In addition, we have to consider the systematic uncertainty in the monitor cross section $Al \rightarrow {}^{24}Na$ of 6.5%.

The monitor reaction ^{27}Al --> ^{24}Na in 'monitor 1' gives excessively large and thus completely incorrect results. This reflects several processes in addition to the nuclear reaction of interest. Such processes include formation of the product of interest by secondary particles. Production by secondaries is clearly related to the target thickness, primary projectile energy and the target materials.

The major reaction, disturbing this monitor reaction, is $^{27}Al(n, \alpha)^{24}Na$. It has a maximum cross section of about 0.1 b near 14 MeV[10] (Fig.3[7, 11]). Neutrons generated in the target and striking the monitoring Al-foils can in principle induce this extra activity due to their large activation cross section in reaction $^{27}Al(n, \alpha)^{24}Na$ at higher neutron energies. In contrast,

protons emitted backwards provide negligible influence as their cross section is relatively low. We estimate the spectrum and the multiplicity of neutrons leaving the target volume in the backward direction and striking the foil. These estimations have been performed using DCM Monte-Carlo simulation (Dubna Cascade-Evaporation Model)[4,8]. As an example, spectra of the neutrons emitted in upstream direction and at monitor 1 and monitor 2 positions for the irradiation of the uranium target with 1.5 GeV protons are given in Fig.4. It is estimated that about 1.75 neutrons per incident proton are passing through monitor 1, and only 0.01 through monitor 2 due to the wide angular distribution. Therefore, the reaction $^{27}Al(n, \alpha)^{24}Na$ disturbs the monitor measurement in monitor 1 considerably, however its influence is negligible in case of monitor 2.

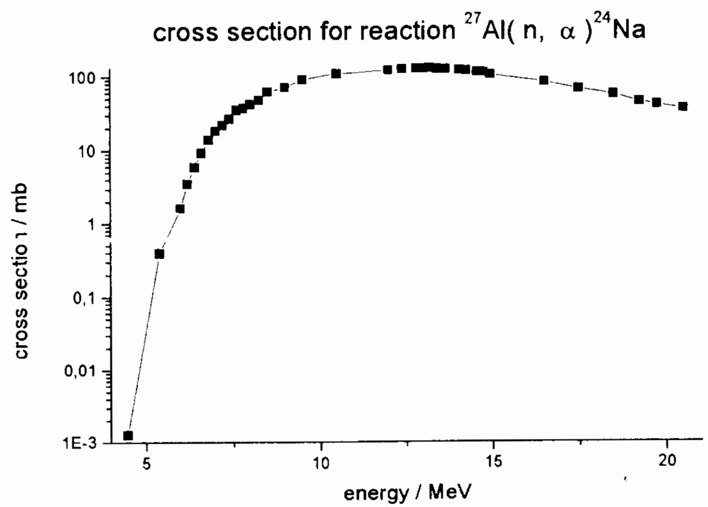

Fig. 3: Excitation function of reaction $^{27}Al(n, \alpha)^{24}Na$[7, 11]

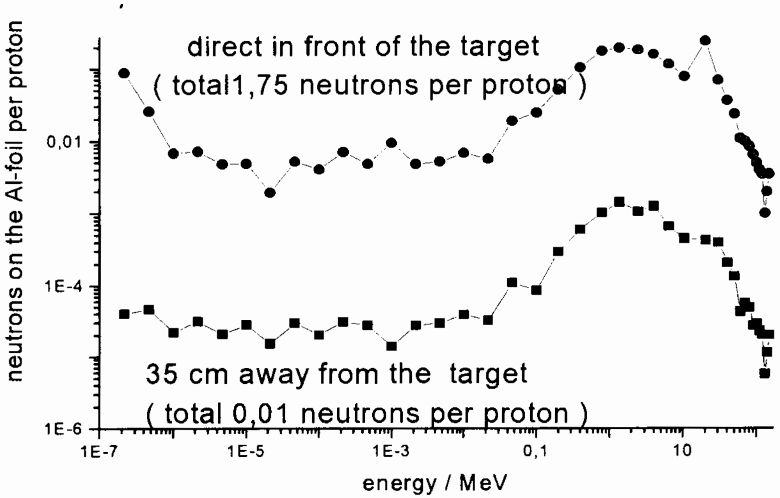

Fig. 4: Spectra of neutrons emitted from thick target and going through Al-monitor 1 and 2. (1.5 GeV p + 20 cm U)

The experimental and calculated influences I of reaction $^{27}Al(n, \alpha)^{24}Na$ on the fluence measurement are given in Tab.2. The influence I is defined as follows:

$$I = {}^{27}Al(n, \alpha)^{24}Na \; / \; {}^{27}Al(p, 3pn)^{24}Na * 100 \, \% \, .$$

The simulation results agree with the experimental ones: the influence I of the reaction $^{27}Al(n, \alpha)^{24}Na$ on the monitor reaction $^{27}Al(p, 3pn)^{24}Na$ in Al-monitor 2 placed 35 cm away from the target is much smaller than that in Al-monitor 1. In the irradiation of uranium with 1.5 GeV proton beam, according to the theoretical estimation, the influence in Al-monitor 2 is less than 5 %, and can be neglected. The Fig. 5 shows that the influence in both Al-monitors 1 and 2 varies with the thickness of lead target bombarded with 1 GeV proton beam. The influence in Al-monitor 2 is always much less than in Al-monitor 1 placed in contact with Pb target.

Tab.2: Experimental and theoretical influence I (in percent) of reaction $^{27}Al(n, \alpha)^{24}Na$ on the monitor reaction $^{27}Al(p, 3pn)^{24}Na$

	I (experimental) / %	I (theoretical.) / %	
experiment	in Monitor 1	in monitor 1	in monitor 2
1.0 GeV p + Pb	68	80	1.3
1.5 GeV p + Pb	99	104	2.3
1.0 GeV p + U	156	154	3.4
1.5 GeV p + U	373	209	4.8

Fig. 6 shows the situation of Al-monitor placed directly in front of target using 1.0 GeV proton beams bombarding different target materials. For a Pb target, if the target would be 0.2 cm thick, the influence of reaction (n, α) could reach more than 7.7 %. For Fe-targets being 0.5 cm thick, the reaction (n, α) introduces less than 10 % influence. For a 20 cm thick Al target, there are only less than 10 % error induced by reaction of (n, α).

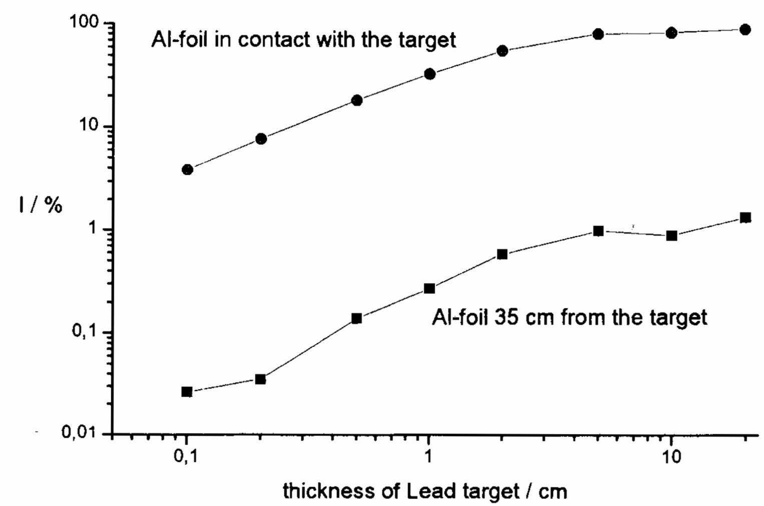

Fig. 5: Calculated influence I in reactions of both monitors (1.0 GeV p + Pb)

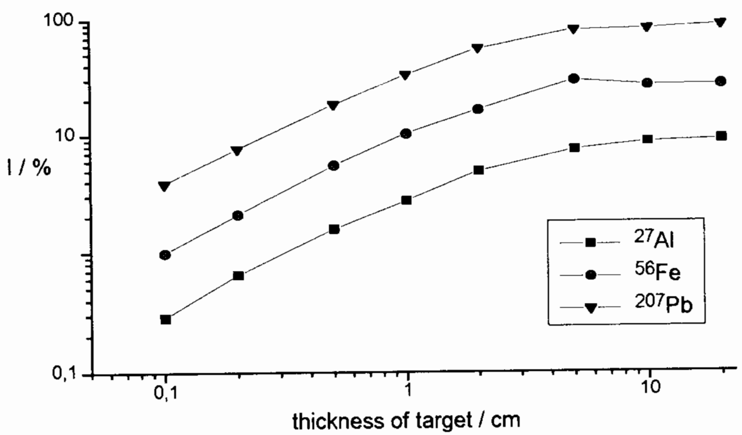

Fig.6: Calculated influence I in monitor 1 for 1.0 GeV protons bombarding ^{27}Al, ^{56}Fe and ^{207}Pb targets

For lead target with thickness less than 0.2 cm it is convenient to study nuclear interactions in the field of high energy particle physics. In the current field of interest (accelerator-driven-transmutation), one always uses a thick lead target. It is impossible to measure a proton beam intensity using the monitor reaction $^{27}Al(p, 3pn)^{24}Na$ when the Al-monitor is placed in close contact to the thick targets, because the flux of secondary particles (mostly neutrons) significantly influences the induced activity.

CONCLUSIONS

The comparison of the values of the proton fluence obtained with different monitoring techniques shows that in case of the monitoring foil placed in close contact with a massive target it is required to use a 1 mm Cu-plate, the reaction $^{nat.}Cu(p, x)^{24}Na$ is used as a radiochemical monitor reaction. Both conventional monitor reactions, $^{27}Al(p, 3pn)^{24}Na$ and $^{nat.}Cu(p, x)^{24}Na$ can be used when the monitor foil is placed 35 cm upstream from the thick target. The influence of reaction $^{27}Al(n, \alpha)^{24}Na$ on the monitor reaction $^{27}Al(p, 3pn)^{24}Na$ was studied theoretically and experimentally in the present work. For Fe- and Pb-target, the target thickness should be less than 0.5 cm and 0.2 cm, respectively, if one uses monitor 1 (i.e. in close contact with the target) for fluence determination.

ACKNOWLEDGMENTS

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REFERENCE

[1] J. B. Cumming, Monitor Reactions for High Energy Proton Beams. Ann. Rev. Nucl. Sci., 13, 261(1963).

[2] K. H. Lieser, Einfuehrung in die Kernchemie, 3rd edition, NY10010-4606(USA), 1991.

[3] R.Brandt, Ch.Gfeller and W.Stoetsel-Riezler. Some Remarks Concerning the Proton Flux Monitor Reaction $^{27}Al(n, 3pn)^{24}Na$. Nucl. Inst. Meth., 62, 108(1968)

[4] J-S. Wan, M. Ochs, R. Brandt, Th. Schmidt, E-J. Langrock, P. Vater, I.G. Abdullaev, J. Adam, V. P. Bamblevskij, V. Bradnova, V. S. Butsev, L. Gelovani, P. G. Golubev, T.G. Gridnev, V. K. Kalinnikov, J. Karachuk, M.I.Krivopustov, B.A.Kulakov, A.N.Sosnin, V.P.Perelygin, A.N. Priemyshev, V.S. Pronskikh, V.I. Stegailov, V.M.Tsoupko-Sitnikov, J.C.Adloff, M.Debeauvais, G.Modolo, R.Odoj, P-W.Phlippen, M.Zamani, K.K.Dwivedi and B.Wilson. Transmutation of Radioactive Waste with the Help of Relativistic Heavy Ions. Kerntechnik, 63(4), 167-177 (1998)

[5] M. Heck, Weitwinkelemission Energiereicher Sekundärteilchen bei der Wechselwirkung Relativistischer Schwerionen mit Kupfer - Target. Dissertation, Universitaet-Marburg, 1992.

[6] R.Brandt, G.Dersch, E.M.Friedlander, G.Haase, M.Heck, V.S.Butsev, M.I.Krivopustov, B.A.Kulakov, E.-J.Langrock, F.Pille, H.H.Gui and E.Ganssauge. Enhanced Production of ^{24}Na by Wide-Angle Secondaries Produced in the Interaction of Relativistic Carbons with Copper. Phys. Rev. C., 45 1194 (1992)

[7] JEF-PC Nuclear Data Bank, 1985

[8] M. Ochs, J-S. Wan, R. Brandt, Th. Schmidt, E-J. Langrock, P. Vater, I.G. Abdullaev, J. Adam, V. P. Bamblevskij, V. Bradnova, V. S. Butsev, L. Gelovani, P. G. Golubev, T.G. Gridnev, V. K. Kalinnikov, J. Karachuk, M.I.Krivopustov, B.A.Kulakov, A.N.Sosnin, V.P.Perelygin, A.N. Priemyshev, V.S. Pronskikh, V.I. Stegailov, V.M.Tsoupko-Sitnikov, G.Modolo, R.Odoj, P-W.Phlippen, R.Hashemi-Nezhad, K.K.Dwivedi, I.V.Zhuk, S.F.Boulyga, E.M.Lomonossova, A.F.Kievitskaja, I.L.Rakhno, S.E.Chigrinov, M.Zamani, J.C.Adloff, M.Debeauvais and B.Wilson. Transmutation Studies on ^{129}I and ^{237}Np using 1.5 GeV, 3.7 GeV and 7.4 GeV protons.
Nucl. Instr. and Meth. in Phys. Res. A, 1999, accepted

[9] W.Westmeier, GAMMAW-Handbuch, Ebsdorfergrund-Moelln, Germany (1991)

[10] H.R.Heydegger, A.L.Turkevich, A.Van Ginnehen and P.H.Walpole. Production of ^{7}Be, ^{24}Na and ^{28}Mg from Mg, Al and SiO_2 by Protons between 82 and 800 MeV.
Phys. Rev. C 14(4), 1506 (1976)

[11] S.Tagesen and H.Vonach, Physics Data - Evaluation of the Cross Sections for the Reaction ^{27}Al(n, a)^{24}Na. ISSN 0344-8401, 1981, Nr 13 - 3.

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Адам И. и др. E13-99-189

Мониторирование пучка протонов высокой энергии. падающих на толстую мишень, с помощью алюминиевых фольг

Изучены реакции $^{27}Al(p,3pn)\,^{24}Na$ и $^{64}Cu(p,X)\,^{24}Na$ как реакции мониторирования пучка при облучении U и Pb мишеней толщиной 21 см протонами с энергией 1,0 ГэВ и 1,5 ГэВ. Влияние реакции $^{27}Al(n,\alpha)\,^{24}Na$ на реакцию мониторирования $^{27}Al(p,3pn)\,^{24}Na$ исследовано экспериментально и теоретически. Во избежание влияния (n,α)-реакции рекомендуется устанавливать алюминиевые мониторы на расстоянии 35 см перед мишенями.

Этот метод можно использовать при изучении трансмутации долгоживущих радиоактивных отходов на ускорителе. При этом использовались мишени из тяжелых элементов, облучаемые протонами с энергией около 1 ГэВ.

Эксперименты проводились в Дубне в Лаборатории высоких энергий Объединенного института ядерных исследований.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1999

Adam J. et al. E13-99-189

Monitor Reactions in Al-Foils for High Energy Proton Beams Bombarding a Thick Target

During the bombardment of U and Pb targets (each 21 cm thick) with protons of energy 1.0 GeV and 1.5 Gev, the reactions $^{27}Al(p,3pn)\,^{24}Na$ and $^{nat.}Cu(p,X)\,^{24}Na$ were studied as monitor reactions. The influence of $^{27}Al(n,\alpha)\,^{24}Na$ on the monitor reaction $^{27}Al(p,3pn)\,^{24}Na$ was investigated experimentally and theoretically. In order to avoid the influence of (n,α) reaction, placing of the Al-monitors 35 cm upstream the massive targets is recommended. This method may be used in Accelerator-Driven-Transmutation (ADT) studies of long-lived nuclear waste, where one always uses a massive heavy element target irradiated with protons at about 1 GeV. The experiments were performed at the Laboratory of High Energies, JINR, Dubna, Russia.

The investigation has been performed at the Laboratory of High Energy, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 1999