RESONANT REACTION WITH A SUPERINTENSE CIRCULATING BEAM

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Abstract

A system for efficient generation of resonance reaction in interaction of the circulating ion beam with a thin internal target is considered. Features of discussed system are high intense space charge compensated circulating ion beam with intensity grater then a space charge limit in near integrable nonlinear focusing system. Ionization energy loss is compensated by inductive electric field. Multiple scattering and energy straggling are compensated by electron cooling with a tabular electron beam. In this method it is possible to compensate an energy loss of circulating particles after crossing the target and have a crossing of resonant energy in every passing of target. For sharp resonance reactions and monoenergetic beam a thin target method can delivery an increase greatly the energy efficiency.

INTRODUCTION

This report is concerned with the production of beams of high-energy narrow-spectrum photons and/or neutrons and a method to use the beams to actively interrogate containers and detect concealed nuclear materials, radiological materials, and chemical explosives. A specific feature of this method is the penetrating nature of the photon or neutron beam coupled with low background radiation, which is important for sensitive detection of well-shielded materials.

Recent technical developments encourage us to revisit nuclear-based gamma ray generation for special nuclear material and explosive detection technology that demonstrated great potential in the early 1990s but lacked the advanced accelerator technology required for practical applications. The most-studied gamma ray resonance absorption (GRA) method provides highly penetrating gamma rays that are strongly and preferentially absorbed in nitrogen, a major constituent of most high explosives [1-4]. Pending the advancement of accelerator technology to meet demands for high-quality, high-intensity proton beams, however, GRA has remained a laboratory curiosity for the most part.

THICK TARGET SYSTEMS

A diagram of resonant gamma ray generation and of its use for detection of concealed material is shown in Fig. 1. The bombardment of a thick solid or liquid target by accelerated particles is the common method to produce high energy nuclear reactions such as excitation, fission or fusion of a nucleus. High-energy particles transmit energy mainly to atomic electrons, and only a small fraction of particles can produce a nuclear reaction before the beam is decelerated below the threshold energy of the reaction. For resonant reactions with a nonzero cross section in the energy window ± Γ around resonant energy W_r , reaction generation takes place only on a very thin layer of the target during the ionization energy loss of particles from energy $W_r+\Gamma$ to $W_r-\Gamma$. The ionization energy loss of particles with energy W and mass M in a substance with a particle mass m and density n in a target distance between x and $x + dx$ is determined by the equation:

$$dW/dx = -AMc^2 mn/2W \, , \tag{1}$$

where, $A=2\ MeV/g/cm^2$, is a specific energy loss by a relativistic particle in a substance with average nuclear mass.

For the resonant reaction $^{13}C(p, \gamma)\ ^{14}N$, generating a 9.17 MeV gamma-ray for resonant excitation of ^{14}N, the resonant proton energy is $W_r = 1.7476\ MeV$, and $2\Gamma = 75\ eV$. The estimated thickness of a carbon target for efficient production of this resonant reaction by a monoenergetic ion beam is:

$$m\, n\, \Delta x = (2\, W_r\, /\, AMc^2) 2\, \Gamma = 1.3\ 10^{-7}\ g/cm^2 \, . \tag{2}$$

The corresponding target thickness in number of particles is $n\ \Delta\ x = 0.6\ 10^{16}\ n/cm^2$. And the number of nuclear reactions $^{13}C(p, \gamma)\ ^{14}N$ with cross section $\sigma = 200\ mbarn$, is $\eta \sim 5\ 10^{-9}$ gamma/proton. The yield of resonant gamma rays in a thick target is very low because resonant reactions are produced only during the loss of very low part of proton energy in the target $2\Gamma / W_r = 4.3\ 10^{-5}$, and all other energy is lost in the target.

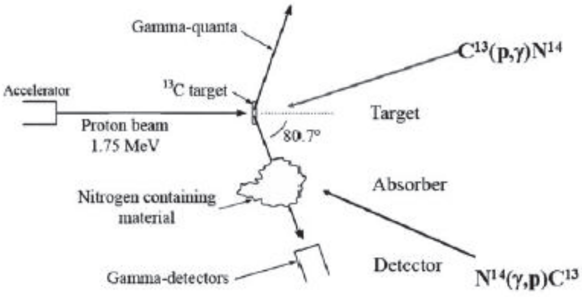

Fig. 1: Diagram of resonant gamma ray generation using a conventional accelerator and solid target to be used for the detection of concealed material.

Through the transmission of the proton momentum to the compound nucleus, and transmission of gamma-quantum momentum, resonantly absorbed by nitrogen, the gamma photons could be emitted only into a conical surface with an angle to the proton direction of $\alpha = 80.7 \pm 2$ degrees. Photons emitted in this cone surface have a very large cross section (2 barn) for nitrogen nucleus excitation, but nitrogen is relatively transparent for gamma rays emitted into other directions. Concentration of nitrogen and other material could be detected by exposure of object by resonant and nonresonant gamma-

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rays and detection of beam resonant attenuation and resonant scattering by special resonant detectors. An example of equipment for exposure and detection of inspected objects is shown in Fig. 2.

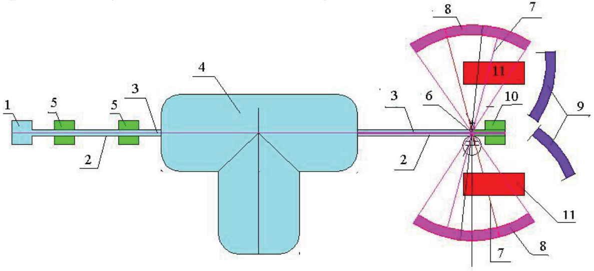

Fig. 2: Schematic of equipment for generation of resonant gamma rays in the reaction $^{13}C(p, \gamma)\, ^{14}N$ with a thick target for the inspection of objects. 1- ion source; 2- beam line; 3- ion beam; 4- accelerator; 5- lenses; 6- thin isotopic target for gamma ray generation; 7- cone of resonant gamma rays; 8- detectors of transmitted rays; 9- detectors of scattered resonant γ- rays; 10- proton beam dump; 11- inspected objects.

An attempt to develop equipment for the GRA method was conducted by a collaboration of TRIUMF and Northrop Grumman Advanced Technology and Development Center [5,6], but reliable operation of the tandem accelerator was not achieved.

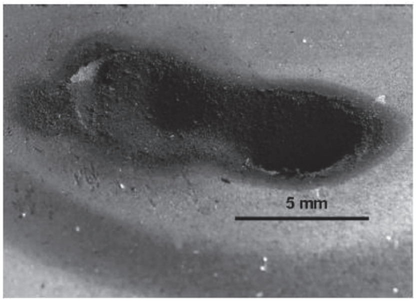

Fig. 3: Graphite target erosion after 10 minutes irradiation by proton beam with energy 1.9 MeV and current 2 mA.

Recently the feasibility of this method was verified by a Los Alamos team in collaboration with the Budker Institute. The resonant gamma rays were generated in interaction of a 1.9 MeV proton beam produced by a Vacuum Insulated Tandem Accelerator (VITA) with a thick ^{13}C target [7]. However, fast erosion of the carbon (graphite) target can be a problem for continuous operation, as shown in Fig. 3. For fast detection of concealed material it is necessary to have a proton current >~10 mA. Real detection systems described in refs. 3-7 use BGO scintillators for efficient detection of 9.1 MeV gamma photons. Some improvements of the resonance gamma ray and neutron generation were proposed in [8,9].

RESONANCE REACTIONS GENERATION WITH CIRCULATING ION BEAMS

The efficiency of resonant gamma ray generation can be increased significantly by using a circulating proton beam interacting with a thin ^{13}C target provided that the ionization energy loss is compensated. Such a circulating proton beam interacting with an internal gas jet target was described in [10-13]. Production of the circulating proton beam with intensity greater than the space charge limit was described in [14-16].

1. Resonant Gamma Ray production by protons hitting a thick ^{13}C target has a low probability, as $\sim 10^{-9}$ γ/p because this resonant reaction is possible only in a very narrow energy window (~100 eV).

2. Using a circulating proton beam with a thin internal target and proper compensation of the ionization energy loss, makes it possible to increase the number of crossings of the resonant energy with a concomitant increase in the number of generated gamma photons.

3. This use of a circulating proton beam with a thin target and RF compensation of the ionization energy loss to increase the number of crossings of the resonant energy was proposed in [17]. A disadvantage of RF compensation of energy loss, a high energy spread in the beam, will be discussed below.

4. In SAIC US patent Number 5,854,531 [18], a storage ring system was proposed with a method for high–yield nuclear reaction production that used accelerated particles accumulated in a storage ring, where the circulating particles interact with a thin isotopic target. For compensation of the ionization energy loss in the target and for circulating beam stabilization, it was proposed to use electron cooling. A low current beam injection with an intensity $I_j \sim 0.1$ mA was proposed to accumulate a circulating beam with current of $I_b \sim 0.25$ A.

That proposed technique [18] of high current beam accumulation is not realistic because the circulating proton beam in these conditions is very unstable. During the slow accumulation of coasting circulating ion beam, a coherent interaction of the beam with electrons trapped by space charge leads to fast development of a strong transverse instability (e-p two stream instability or electron cloud effect) with very efficient transformation of longitudinal beam energy to the energy of transverse betatron oscillations, resulting in fast beam loss [10-13]. In a racetrack storage ring, very similar to the one proposed in this patent, that instability had a threshold current $I_t \sim 3$ mA. In this situation, electron cooling can only increase the instability and decrease the accumulated current. The friction force of electron cooling is relatively weak, not enough for compensation of ionization energy loss in the optimal target. For compensation of energy loss in the target, it is necessary to use an acceleration system such as an induction acceleration system or RF acceleration system. Electron cooling is useful for reducing the energy spread created by energy loss straggling and angle spread created by multiple scattering in target. For these purposes, it is better to use a hollow tube-like electron beam with axisymmetric cathode and collector located around the proton beam in a straight section of the racetrack. This geometry enables use of much higher electron current density and faster electron cooling.

RING FOR RESONANT PHOTONS AND NEUTRONS PRODUCTION

A schematic diagram of a possible ring appropriate to resonant photon production that incorporates electron cooling discussed in [19] is shown in Fig. 4.

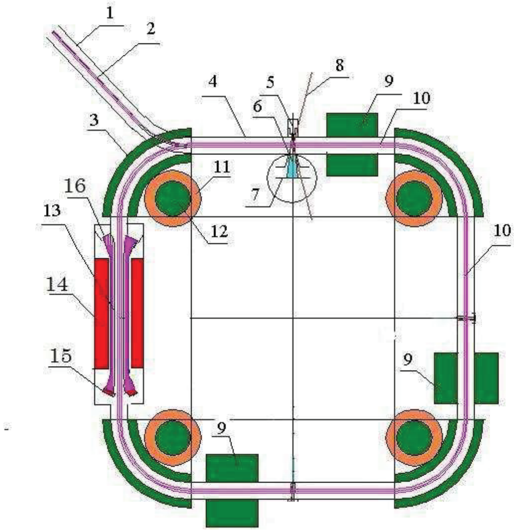

Fig. 4: Schematic of resonant reaction production using a circulating proton beam with thin targets accompanied by electron cooling. 1- beam line for injecting H- beam; 2- injecting beam of H-; 3- bending magnets; 4-vacuum chamber of storage ring; 5- generator of supersonic jet- stripping, reaction target; 6- supersonic jet, stripping-reaction target; 7- pump-recirculator of target jet; 8- cone of resonant gamma rays; 9- iron core for inductor for compensation of beam energy loss in first target; 10-circulating proton beam; 11- magnetic coil; 12- yoke of bending magnet; 13-cylindrical hollow electron beam; 14- solenoid of electron cooling system; 15- cathode of electron cooling beam; 16- collector of electron beam.

In the Fermilab design of a storage ring [20] with nonlinear focusing, charge exchange injection can be used. For an energy of 10 MeV it is possible to use a supersonic gas jet as a stripping target as it was done in the small scale proton storage ring in BINP [10-16]. An RFQ and a small linac can be used as the injector with H^- beam ~0.1 A, 10 MeV. A circulating proton beam ~10 or 100 A can be accumulated.

Such a beam can be used for realization of resonance reaction induced by circulating ions in a thin internal target as shown in Fig. 4. Electron cooling can be used for scattering and energy spread compensation. Some other methods of space charge compensation, as discussed in refs. [8,17] can be used for improving operation. The plasma growth during the accumulation of a super intense beam was discussed in [21]. Some possible realizations of circulating beam with intensity above the classical space charge limit were discussed in [22]. A comprehensive review of e-p instability in different accelerators and storage rings was presented in [23] and references. Theoretical estimation of self-stabilization is presented in [24]. For realization of this project it is possible to use some developments for high intensity beam production produced for Project X at Fermilab [25].

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